NOAA Technical Memorandum
NMFS-SEFC-43

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ANNUAL REPORT TO EPA

Environmental Assessment of Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico, 1978 - 1979

A report to the Environmental Protection Agency on work conducted under provisions of Interagency Agreement EPA-IAG-D5-E693-E0 during 1978 - 1979.

Volume IX

FATE AND EFFECTS MODELING

SOUTHEAST FISHERIES CENTER
GALVESTON LABORATORY

DECEMBER 1980

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southeast Fisheries Center
Galveston Laboratory
Galveston, Texas 77550

NOAA Technical Memorandum NMFS-SEFC-43

Environmental Assessment of Buccaneer Gas and Oil Field In the Northwestern Gulf of Mexico, 1978-1979

VOL. IX - SOURCES, FATE AND EFFECTS MODELING

BY

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A report to the Environmental Protection Agency on work conducted under provisions of Interagency Agreement EPA-IAG-D5-E693-E0 during 1978-1979.

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GUIDE TO USERS OF THE ANNUAL REPORT

Volume I (SYNOPSIS/DATA MANAGEMENT) of the Annual Report is designed to be used as a briefing document and as a key to more detailed scientific and technical information contained in Volumes II through X. Objectives, methods and results for each work unit are summarized in greatly abbreviated form within Volume I to facilitate dissemination of information. Thus, Volume I can be used alone or as a reference to companion Volumes II through X. Complete citations for literature cited in Volume I can be found in the Volumes II through X in which the detailed work unit reports are presented.

It is hoped that such an approach to environmental impact information dissemination will make the Annual Report a more useful and widely read document.

FOREWORD

Increased petroleum development of the outer continental shelf (OCS) of the United States is anticipated as the U.S. attempts to reduce its dependency on foreign petroleum supplies. To obtain information concerning the environmental consequences of such development, the Federal Government has supported major research efforts on the OCS to document environmental conditions before, during, and after oil and gas exploration, production, and transmission. Among these efforts is the Environmental Assessment of Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico, a project funded by the Environmental Protection Agency (EPA) through interagency agreement with the National Oceanic and Atomospheric Administration (NOAA) and managed by the National Marine Fisheries Service (NMFS), Southeast Fisheries Center (SEFC), Galveston Laboratory, in Galveston, Texas. Initiated in the autumn of 1975, the study is now in its last year. Its major products have been annual reports disseminated by the National Technical Information Service, data files archived and disseminated by NOAA's Environmental Data and Information Service, and research papers written by participating investigators and published in scientific or technical journals. Results have also been made available through EPA/NOAA/NMFS project reviews and workshops attended by project participants, and various governmental (Federal and State), private, and public user groups. The final products will be milestone reports summarizing the findings of the major investigative components of the study.

Objectives of the project are (1) to identify and document the types and extent of biological, chemical and physical alterations of the marine ecosystem associated with Buccaneer Gas and Oil Field, (2) to determine specific pollutants, their quantity and effects, and (3) to develop the capability to describe and predict fate and effects of Buccaneer Gas and Oil Field contaminants. The project uses historical and new data and includes investigations both in the field and in the laboratory. A brief Pilot Study was conducted in the autumn and winter of 1975-76, followed by an extensive biological/chemical/physical survey in 1976-77 comparing the Buccaneer Gas and Oil Field area with adjacent undeveloped or control areas. In 1977-78, investigations were intensified within Buccaneer Gas and Oil Field, comparing conditions around production platforms, which release various effluents including produced brine, with those around satellite structures (well jackets) which release no effluents. In 1978-79, studies around Buccaneer Gas and Oil Field structures focused on (1) concentrations and effects of pollutants in major components of the marine ecosystem, including seawater, surficial sediments, suspended particulate matter, fouling community, bacterial community, and fishes and macro-crustaceans, (2) effects of circulation dynamics and hydrography on distribution of pollutants, and (3) mathematical modeling to describe and predict sources, fate and effects of pollutants. The final year, 1979-80, of study is continuing to focus on items (1) and (2) and on preparation of the milestone reports which will represent the final products of this study.

This project has provided a unique opportunity for a multi-year investigation of effects of chronic, low-level contamination of a marine ecosystem associated with gas and oil production in a long-established field. In many respects, it represents a pioneering effort. It has been made possible through the cooperation of government agencies, Shell Oil Company (which owns and operates the field) and various contractors including universities and private companies. It is anticipated that the results of this project will impact in a significant way on future decisions regarding operations of gas and oil fields on the OCS.

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INTRODUCTION

Location of Study Area

The area selected for study is the operational Buccaneer Gas and Oil Field located approximately 49.6 kilometers (26.8 nautical miles) south southeast of the Galveston Sea Buoy off Galveston, Texas (Figure 1). This field was selected in 1975 as the study area because: (a) the field had been in production for about 15 years, which time had allowed full development of the associated marine communities; (b) it was isolated from other fields which facilitated the selection of an unaltered area (for comparison) within a reasonable distance of the field; (c) it produced both gas and oil that represented sources of pollutants from marine petroleum extraction; (d) its location simplified logistics and reduced the cost of the research; and (e) the Texas offshore area had not been fully developed for gas and oil production but was expected to experience accelerated exploitation in the future.

Operation History of Buccaneer Field

Buccaneer Field was developed by Shell Oil Company in four offshore blocks leased in 1960 and 1968 as follows:

Year	Lease Number	Block Number	Acreage	Hectares
1960	G0709	288	2,790	1,129
1960	G0713	295	4,770	1,930
1960	G0714	296	4,501	1,821
1968	G1783	289	2,610	1,056

In development of the field, 17 structures were built; two are production platforms, two are quarters platforms, and 13 are satellite structures surrounding well jackets. Initial exploratory drilling began about mid-summer of 1960 with mobile drilling rigs. When (as the result of the exploratory drilling) proper locations for platforms were selected, the permanent production platforms were constructed.

There have been no reports of major oil spills from this field. There have been some reported losses of oil due to occasional mechanical failure of various pieces of equipment. The largest reported spill was three barrels in 1973. The reported oil spill chronology and quantity for Buccaneer Field is as follows:

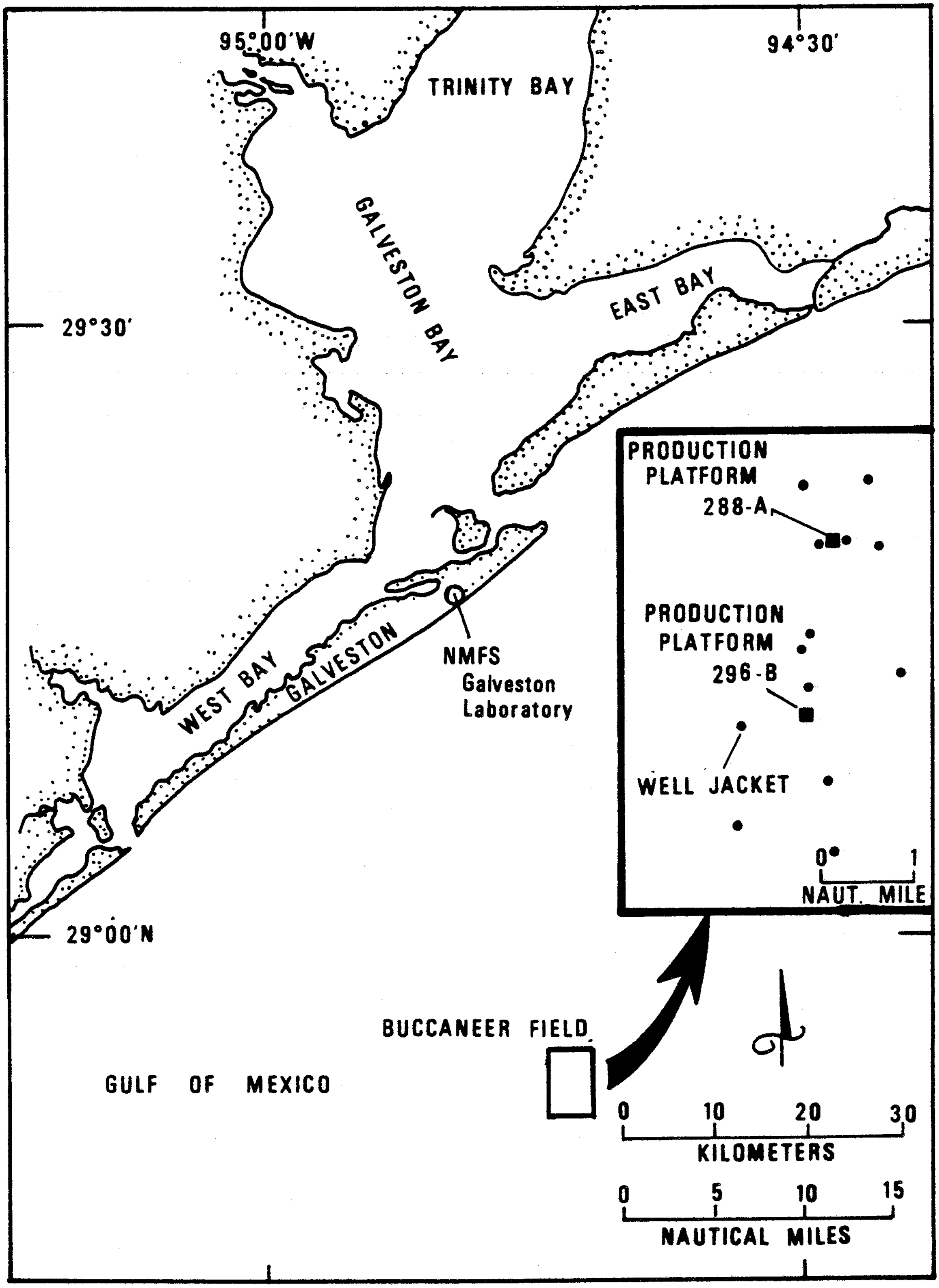

FIGURE 1. LOCATION OF BUCCANEER FIELD

Date	Source	Amount Barrels	Liters
September 1973	Platform 296-B	0.5	79
November 1973	Unknown	3.0	477
July 1974	Platform 296-B	0.5	79
August 1974	Platform 296-B	1.7	265
September 1975	Platform 288-A	0.2-0.4	38-56
Totals		5.9-6.1	938-956

Buccaneer Field first began operations with the production of oil. Later, when significant quantities of gas were found, the field began producing both oil and gas and has continued to do so to date.

The production platforms and satellites (well jackets) are connected by a number of pipelines with a 50.8 centimeters (20-inch) diameter main pipeline connecting the field to shore. All of the pipelines that are 25.4 centimeters (10 inches) or greater in diameter are buried. The Blue Dolphin Pipeline Company was granted a pipeline permit (No. G1381, Blocks 288 and 296) in 1965 and has operated the pipeline since its construction.

Buccaneer Field occupies a limited area (about 59.3 km^2; 22.9 sq. statute miles) leased in the northwestern Gulf of Mexico. Four types of structures are located in Buccaneer Field: production platforms, quarters platforms, satellites (well jackets), and flare stacks. These are shown in Figure 2, which is an oblique aerial photograph of production platform 288-A and vicinity within Buccaneer Field. A map of Buccaneer Field, (Figure 3) depicts the locations of platforms and satellites within the field.

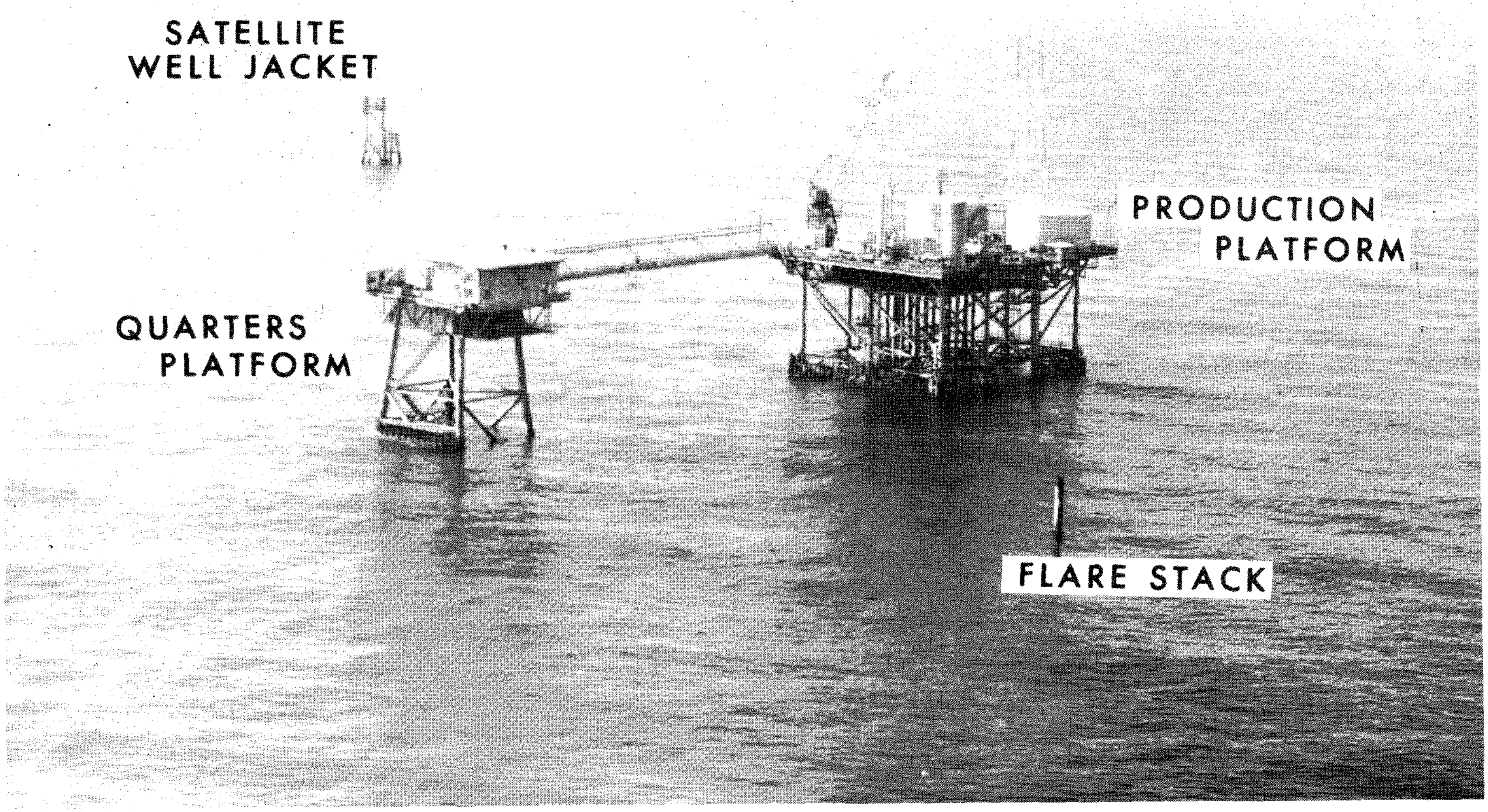

FIGURE 2. BUCCANEER FIELD STRUCTURES

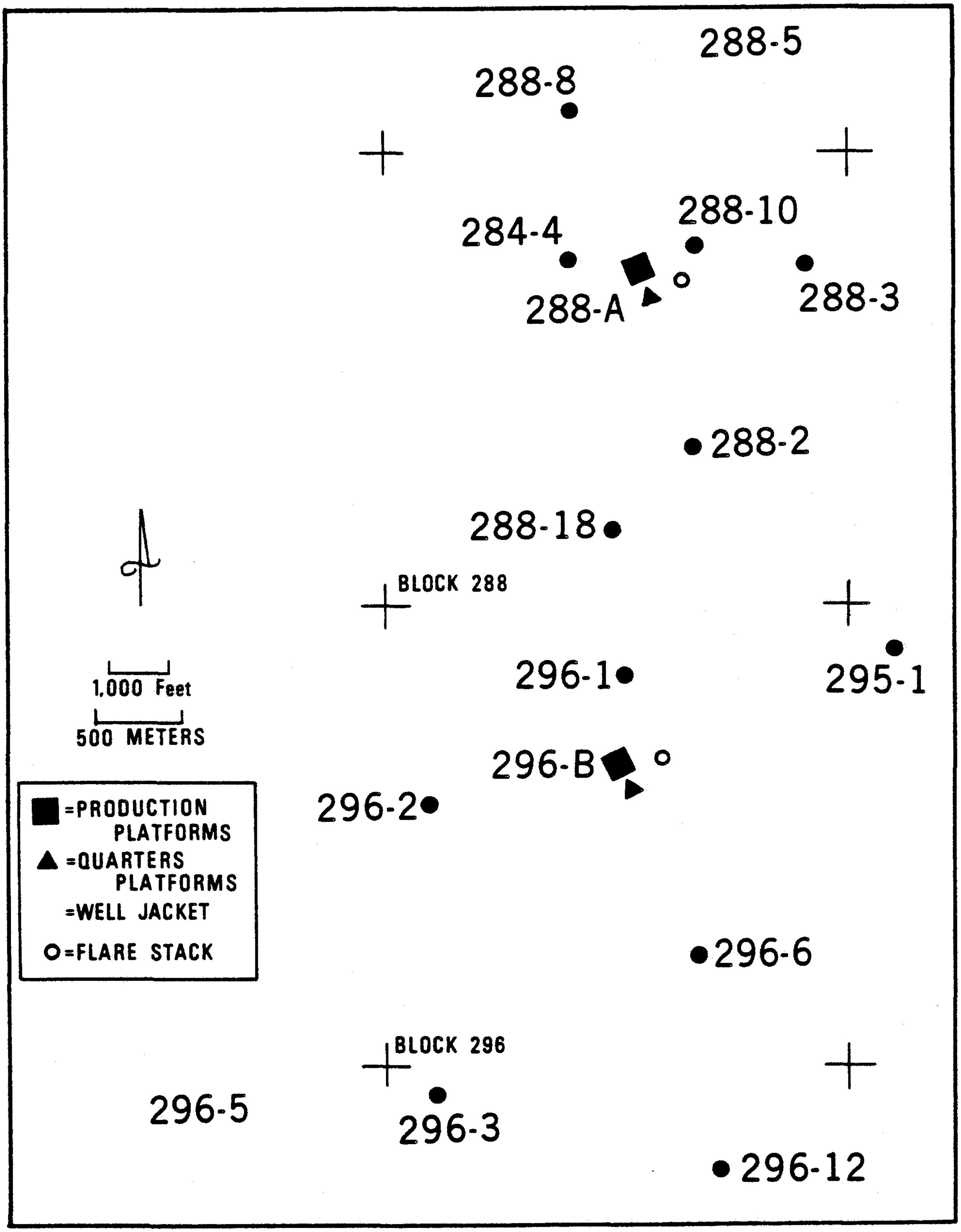

FIGURE 3. SHELL OIL COMPANY'S ALPHANUMERICAL IDENTIFICATION OF BUCCANEER GAS AND OIL FIELD STRUCTURES

WORK UNIT 2.5.1 - SOURCES, FATE AND EFFECTS MODELING

Science Applications, Inc.

K. Fucik, Ph.D.
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ABSTRACT

A model was developed for the Buccaneer gas and oil field that integrated biological, chemical (hydrocarbon), and physical submodels. State-of-the-art flow analysis techniques were used to describe the structure and function of the system. Five compartments consisting of phytoplankton, zooplankton, plankton feeders, fouling flora, and fouling fauna were identified as being system importers. Fouling feeders, particulates, the benthos, benthic feeders, and large predators compartments are exporters from the system.

Two distinct assemblages were identified based on the origin of the material that was stored in the compartments. The major portion of the biomass stored in the zooplankton, plankton feeders, particulates, benthos, benthic feeders, and large predators originates in the phytoplankton. However, the fouling flora provides the primary source of carbon for the pathway that includes the fouling fauna and fouling feeders. Nevertheless, phytoplankton contribute a significant source of carbon to this assemblage. This may be due to the feeding behavior of the barnacles which dominate the fouling fauna. Large predators also appear to be opportunistic feeders although relying predominantly on the pelagic/benthic species. Particulate matter in the form of fecal material and dead and decaying organisms derived from the platform is not a significant source of carbon to the overall system suggesting that detrital materials from the fouling community are internally cycled.

Hydrocarbons discharged from the platform are rapidly dispersed from around the platforms. However, the hydrocarbon model suggests that the hydrocarbons can be transported long distances as only a 10% loss is estimated over a 24-hr. period. Transport of hydrocarbons into the sediments around the platforms appears to occur through incorporation of fecal material or attachment to sulfur particles.

Different routes (i.e., from the sediments versus direct uptake from the water) of contaminant uptake may exist for barnacles as

opposed to other members of the fouling community. However, there are no large accumulations or evidence of biological magnification of hydrocarbons in the Buccaneer field biota. This suggests that any accumulated hydrocarbons are being rapidly and effectively depurated or metabolized.

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INTRODUCTION

Three major multidisciplinary studies have been conducted in the Gulf of Mexico that were concerned with the effects of offshore oil and gas development on the surrounding marine ecosystems. The first of these studies took place off the Louisiana coast just west of the Mississippi delta. The results of the Offshore Ecology Investigation (OEI) have recently been published (Ward et al. 1979). A similar BLM-sponsored study was conducted east of the delta from 1977 to 1979. The results of this study are presently being evaluated (R. Defenbaugh, Bureau of Land Management, New Orleans).

The Buccaneer gas and oil field study began with a pilot survey in November 1975 and was followed by an interdisciplinary program involving physical oceanography, geology, chemistry, and biology during the next four years. The Buccaneer program differs from the other oil field studies in that ecosystems modeling has been used to aid in the synthesis and integration of the disciplinary data.

This work unit was preceded by a number of different modeling efforts. Gallaway et al. (1976) developed a conceptual model of the Buccaneer system. A simulation model was later constructed based on the conceptual model and which emphasized the biological components of the system (Gallaway and Margraf 1979). Middleditch et al. (1979) used empirical data to simulate the fate of hydrocarbons at the air/sea interface, in the water column, and in the sediments of the Buccaneer field. A hydrodynamic model was also developed which was used to relate the dispersion of introduced oil to measured physical parameters in the Buccaneer system (Smedes et al. 1980).

The goal of our modeling effort was to provide an understanding of the structure and function of the Buccaneer ecosystem. Based on data collected between 1976 and 1979 in the Buccaneer field, an overall model of the Buccaneer system was developed which combined physical, chemical, and biological submodels. The basic structure of the model and the results of the modeling effort are discussed in the following report.

GEOPHYSICAL, CHEMICAL, AND BIOLOGICAL CHARACTERISTICS OF THE BOF

The following section summarizes the findings of the disciplinary studies conducted from 1976 to 1979 in the Buccaneer field. These data were also used in the construction of the Buccaneer oil field (BOF) model.

Geophysical Parameters

Sediments

The sediments were quite variable within the area with most consisting of greater than 50% sand, reflecting a high energy bottom condition (Anderson *et al.* 1977). The four sediment facies recognized in the area were sand, clayey sand, silty sand, and sand-silt-clay. The northeastern portion has a fifth sediment type consisting of gravel-sized shell debris. Few sedimentary structures were indicated by X-radiographic analysis but the sediments showed extensive evidence of reworking due to biological activity.

Sediment samples within 113 m of Platforms 288-A and 296-B were sandier than the surrounding sediments and show considerable variation in sand/mud ratios. This may have reflected bottom scouring as a result of eddies created by currents flowing past the legs of the platforms (Anderson *et al.* 1977; Behrens 1977; Brooks *et al.* 1980).

Behrens (1977) concluded that the most obvious physical effect of the oil field is the erosion of the sediments within the field. Radiocarbon dating has provided estimates of this erosion to range from 7 cm to 1 m. Sedimentation occurs at a rate of 0-2 cm/100 years. Behrens suggested that with erosion predominating over deposition, any carbonaceous pollutants would more likely accumulate outside of the field than within it.

Brooks *et al.* (1980) found slightly higher rates of sediment deposition in the BOF than those mentioned above. These authors found rates of 1.5 to 2.1 mm/yr on the northern side of the platform with rates on the southern side estimated at 3.6 mm/yr. They suggest that there is a down-current transport of materials either supplied or resuspended by the platform operations in the Buccaneer field.

The heavy mineral assemblage of the Buccaneer field is consistent with results expected for this area of the Gulf (Anderson et al. 1977). The sediments contain less than 0.50% by volume heavy minerals with hornblende being the most commonly occurring mineral (approximately 50%). Epidote and pyroxenes constitute about 15% each of the heavy mineral assemblage. The results are characteristic of a transition zone between mineralogic provinces with sediments derived from the Colorado, Mississippi, and Rio Grande Rivers and from relict deposits. Similarly, the clay and nonclay mineralogy is similar to clay suites from the Texas coast. The clay mineralogy consists of approximately 58% expandable clays (primarily montmorillonite), 29% illite, and 12% kaolinite. A variation in the "crystallinity" of the expandable clay phases may be due to the presence of drilling muds. This is suggested by concentrations of barium (Ba) around the platforms that are higher than concentrations in control areas (Wheeler et al. 1980). It is likely that the source of the Ba is the barite ($BaSO_4$) which is a major constituent of drilling muds (Perricone 1980).

Scrudato (1976) found that organic carbon levels in the sediments were fairly uniformly distributed throughout the BOF area. Behrens (1977) found that organic carbon in the sediments was low (ranging from 0.1% to something less than 1%) in comparison to other similar areas with the highest concentrations towards the north end of the BOF. Brooks et al. (1980) observed a decreasing gradient in both organic and inorganic carbon away from Platform 288-A. During the summer, the carbon gradients tended to be oriented towards the northeast, probably as a result of the prevailing east-northeast bottom currents at this time (Armstrong and Hamilton 1979). The carbon contours during the winter indicate a southerly flux of carbon. This finding is consistent with the 180° current shift which occurs in September and lasts through the winter (Armstrong and Hamilton 1979).

Carbonates measured in the sediments of the BOF by Scrudato (1976) ranged from a maximum of 18.7% to a minimum of 3.7%. The average carbonate concentration was 8.7% with most of the carbonate being derived from shell fragments. Brooks et al. (1980) also observed a high percentage of $CaCO_3$ in samples taken from beneath the platform, probably reflecting a contribution from the fouling communities on the platform.

Hydrography

Temperature and salinity of the waters of the Buccaneer field are influenced by air temperatures, surface winds, oceanic currents, and freshwater inflow from the Galveston Bay-Trinity River complex (Martin 1977). Nowlin (1972) has also suggested that runoff from the Mississippi and Atchafalaya Rivers may give rise to a narrow band of low salinity water that can be carried over the Texas shelf as far south as 26° south latitude. Based on data compiled from various work units in the Buccaneer program, the highest water temperatures occurred in July-August with the lowest being recorded in January-February. Temperature ranged from about 13°C to 31°C in the surface waters and from 12°C to 29°C at the bottom. Surface salinity was lowest during the spring (27 ‰) and highest during the winter (36 ‰). Danek and Tomlinson (1980) noted that salinity generally increased from the north to the south in the BOF. They suggested that this pattern is perhaps due to the fact that the BOF is located in a mixing zone between fresher coastal waters and more saline offshore waters. These authors also observed both temperature and salinity gradients through the water column on a seasonal basis.

Danek and Tomlinson (1980) observed no obvious trends in the spatial distribution of dissolved oxygen. Concentrations generally ranged from 4.0 to 6.0 ppm although they reached concentrations of 8.1 to 9.1 ppm during a February, 1979 sampling trip. An oxygen depleted layer of cool water was observed in May, 1979 in the nepheloid layer near the bottom.

Armstrong and Hamilton (1979) measured prevailing currents to the northeast (upcoast) during the summer months (May-August) but toward the southwest (downcoast) during the rest of the year. Buoy movements indicated no vertical structure in the current patterns although Armstrong and Hamilton observed layers of contrasting flows during the summer. They suggested that this layering effect may have been due to a high river discharge which seemingly produced a downcoast, geostrophic current. Local winds were generally the main driving force for the observed circulation patterns.

Danek and Tomlinson (1980) list the large-scale circulation of the Gulf, regular tidal changes, wind, river discharges, density gradients, and meanders from deep water currents as factors which influence and create a variable current system in the Buccaneer field area. These authors, unlike previous observations, usually observed the currents moving to the southwest; however, currents were variable in July with periods of easterly flow. Current direction was uniform with depth although there was an approximate 50% reduction in speed from surface to bottom (Table 1). However, the authors observed that current speeds were of sufficient magnitude (more than 2% of the time in summer and more than 5% of the time) to readily resuspend unconsolidated bottom sediments.

Based on the oceanographic measurements made in the Buccaneer field, Smedes et al. (1980) developed a hydrodynamic model for the area which indicated that currents would rapidly disperse small quantities of pollutants but could transport them over long distances.

Suspended Particulates

Danek and Tomlinson (1980) measured an average total suspended solids (TSS) concentration between 1 and 2 mg/l. The highest value was recorded in July (12 mg/l) and the lowest in October (1 mg/l). Using these estimates, the authors calculated a TSS flux through the study area of 2 gm/sec-m of water surface. The TSS values were generally higher than those measured by Brooks et al. (1980).

Brooks et al. (1980) conducted a survey of suspended particulates in the water column in the Buccaneer field. A bottom nepheloid layer was observed in all seasons except winter when suspended particulate concentrations were uniformly distributed through the water column (Table 2). Anderson et al. (1979) observed the nepheloid layer during the summer and early fall. This indicates strong turbulent mixing and low water column stability during the winter. A surface nepheloid layer observed in the spring was attributed to freshwater runoff from coastal bays. During the fall, the bottom nepheloid layer occupied as much as half of the water column, probably due to increased turbulent mixing.

Clay was the dominant particulate material during all seasons although the composition of the suspended particulates varied seasonally (Brooks et al. 1980). The particulate organic fraction was composed almost entirely of cellular material (phytoplankton, zooplankton, and/or bacteria) (Table 2). Overall, the cellular material constituted 20-35% of the suspended particulates; during the winter this ratio increased to 50% due to an increase in phytoplankton production (Brooks et al. 1980). Phytoplankton accounted for essentially all of the particulate organic carbon measured in the water column at this time.

Chemistry Parameters

Environmental Chemistry -- Nutrients

Nutrients (nitrates, phosphates, silicates) were measured by Brooks et al. (1980). Nitrate concentrations were highest in the spring but were fairly uniform during the rest of the year (Table 3). Phosphate concentrations were highest in the fall and uniform during the rest of the year. Silicates were highest in the fall in the surface waters and in the spring in the bottom waters; the lowest levels were recorded in the winter. These patterns are somewhat different from those expected for this area (i.e., maxima in late winter and spring and minima in the summer).

Pollutant Chemistry -- Hydrocarbons

Oil and Produced Water Samples. Middleditch and West (1980) characterized the oil and brine produced in the Buccaneer field. Alkanes from C_{12} to C_{36} accounted for 18% of the crude oil by weight with naphthalene and alkylnaphthalenes accounting for 2.6% of the total hydrocarbons. The Buccaneer crude had an average odd-even preference (OEP) of 0.86 and mean *n*-heptadecane/pristane and *n*-octadecane/phytane ratios of 1.20 and 4.46, respectively.

Alkane concentrations in the brine averaged 2-3 ppm. Based on an average brine discharge of 1000 barrels per day, this equates to a mean daily alkane discharge of 382 grams (Middleditch and West 1980). Benzene was the major volatile identified in the brine (30.5% of the total volatiles) while the C_3- and C_4-benzenes were the highest in the aromatic fraction (24.2 ppb and 23.9 ppb, respectively, of a total aromatic content of 104.2 ppb). Benzene, toluene, and ethylbenzene together accounted for 64% of the volatile fraction.

Sulfur content of the brines averaged 0.13% for the year (Middleditch and West 1980) making it the major pollutant released in the Buccaneer field.

Water. Hydrocarbon levels have been reported for the water column by Middleditch *et al.* (1979b) and Middleditch and West (1980). Alkane distributions are influenced by wind and current directions and are rapidly dispersed and diluted in the Buccaneer field. Only 34% of the total alkanes measured in the water column during the summer, 1978, were found between 8 m and 50 m from the discharge; in the fall, only 1.4% of the total alkanes were found beyond 3 m from the discharge. However, Middleditch *et al.* (1979a) reported low levels of petroleum alkanes at distances up to 10 km from the center of the Buccaneer field. Middleditch *et al.* (1979b) have reported that alkane concentrations in the waters of the Buccaneer field are similar to those previously reported for the eastern Gulf of Mexico and the Caribbean Sea.

Sediments. During the pilot study of the Buccaneer program, hydrocarbon levels (indicative of petroleum contamination in the sediments could be found at only one station near (306 ppm) Platform 288-A (Giam 1976). During subsequent years, however, Middleditch et al. (1979b) and Middleditch and West (1980) have observed concentration gradients of petroleum hydrocarbons extending out from the platforms but which were much less than the 306 ppm measured by Giam. Concentrations had generally decreased by one to two or more orders of magnitude within 50 m of the platform, however. The distributions of these hydrocarbons seem to follow prevailing currents and to be variable on both seasonal and daily time scales. During sampling in 1977-78 the concentrations in the sediments were higher in the winter (22-23 ppm) than in the summer (1.7-17 ppm). Some of this variability may be due to the active physical environment which can rapidly resuspend and redeposit bottom sediments in the area. However, the data is too limited to suggest any definite conclusions regarding the overall variability observed.

Biota. Hydrocarbon analyses were conducted on nearly all phyla found in the Buccaneer field except for phytoplankton and macroalgal phyla (Middleditch et al. 1979b; Middleditch and West 1980). While petroleum hydrocarbons were identified in many of the organisms tested, the levels were generally near background levels and found only in those organisms around the production platforms. Among the more significant observations were:

- high concentrations of fresh oil in fouling mat samples below the discharge at Platform 296B;
- barnacles generally had only negligible or low concentrations of weathered oil;
- among the large fish, sheepshead (*Archosargus probatocephalus*) had the highest petroleum alkane concentrations; the plankton-feeding spadefish (*Chaetodipterus faber*) had the lowest concentrations; the cryptic crested blennies (*Hypleurochilus germinatus*) had the highest alkane concentrations of all the fish;

- evidence of petroleum contamination was generally not observed in shrimp although a few contaminated samples were collected in areas adjacent to the platforms.

Pollutant Chemistry -- Trace Metals

Sediments. In comparison to trace metals concentrations measured during the BLM South Texas Outer Continental Shelf Study, four metals (Ba, Pb, Zn, and Sr) were present in higher concentrations in the Buccaneer field sediments (Anderson *et al.*, 1979). The authors suggest that the sources for the high levels of Pb, and Zn can probably be related to the drilling structures, the sacrificial electrodes used on the structures, and the metal debris on the seafloor around the structures. Wheeler *et al.* (1980) found that only Ba, Cd, and Sr occur at significantly higher concentrations around the platforms than in the rest of the Buccaneer study area (Table 4).

Tillery (1980) observed distinct concentration gradients for Ba, Cd, Cr, Cu, Mn, Pb, Sr, and Zn extending outward from both Platform 288-A and 296-B. The distribution of these trace metals concentrations did not correlate with the hydrated iron fraction or the sediment grain size, however, which suggested an input from the platforms or the production activities. Concentrations in the sediments were highest in the summer and lowest in the winter and probably reflect sediment resuspension.

Tillery (1980) attributed the high levels of strontium in the sediments to the formation waters discharged from the platforms. Strontium levels in the discharge water at Platform 288-A average 47.5 ppm Sr and at Platform 296-B 33 ppm Sr. Wheeler *et al.* (1980) measured Ba and Sr levels that were much higher in the produced brine from the platforms than that which occurs naturally in seawater. Concentrations of the other trace metals in the produced brine were comparatively lower. Seawater samples were also low in trace metals. Enrichment of the strontium in the sediments may have been due to the uptake of Sr by calcium carbonate-secreting organisms whose shells were present in most samples. This was also suggested by Wheeler et al. (1980) who noted a strong correlation between Ba and Sr and carbonate content (0.80 for Ba and 0.87 for Sr). They also suggested that the higher Ba and Sr values in the sediments around the platforms may have been due to the greater availability of these metals in the seawater near the brine discharges.

Biota. Anderson et al. (1979) measured trace metal concentrations in fish, barnacles, plankton and benthic invertebrates from the Buccaneer field. The barnacles had higher concentrations than the fish (Table 5). Barnacles collected near the discharge did not have higher trace metals concentrations than barnacles collected away from the discharge. Triggerfish and sheepshead had higher concentrations of Fe and Zn than the other fish species analyzed. The triggerfish and sheepshead feed primarily on the fouling communities. In comparison to species collected during BLM's south Texas OCS studies, Buccaneer field fish had higher levels of Cr, Cu, and Zn; plankton from the BOF had higher levels of Cd, Cu, Mn, Pb, and Zn.

Tillery (1980) saw no significant differences in trace metal concentrations from sheepshead, spadefish, or longspine porgy collected from platform or well jacket (control) stations but seasonal differences in Cd, Cr, Cu, Fe, and Sr in sheepshead and spadefish were observed. Hg was also seasonally variable in spadefish. Longspine porgy from the Buccaneer field had higher concentrations of Fe and Pb than did samples of longspine porgy collected in the south Texas BLM study. No significant increases in metal concentrations were observed in the fouling mat or barnacles from the platforms versus control structures.

Biological Parameters

Phytoplankton. No specific studies were conducted on phytoplankton in the Buccaneer field. However, Brooks et al. (1980) collected some seasonal observations on chlorophyll-a levels in the area. Chlorophyll-a was highest in the surface waters during the winter and lowest in the summer. Except for the summer, concentrations through the water column were similar. The summer pattern probably reflects the formation of the thermocline and reduced mixing. These patterns are similar to those observed in other Gulf coastal regions (e.g., Fucik and El-Sayed 1979).

Bacteria. Microbial populations in the Buccaneer field were delineated by Sizemore *et al.* (1979) and Sizemore and Olsen (1980). Generally, bacterial numbers (based on total viable counts) ranged from 63 to 1600 per ml in the water and from 4.9×10^5 to 1.7×10^7 organisms per gram dry weight of sediment. The bacterial numbers were relatively similar during the summer, winter, and spring. Counts in the water during the fall were tenfold lower than during the other seasons although sediment counts were in the same range. The bacterial counts were similar from both the Buccaneer field and control areas.

Pseudomonas, *Vibrio*, *Aeromonas*, *Acinetobacter* and *Moraxella* were common in the area. *Aeromonas hydrophilia* was consistently associated with diseased fish collected in the oil field. Oil degrading and sulfur oxidizing bacteria were more common in the oil field than at control sites (Table 6). This is likely in response to the input of petroleum and sulfur through the brine discharges. The percent of oil degraders and sulfate-reducers varied seasonally. Sulfate-reducing bacteria were especially abundant in the sediments around the platforms.

Zooplankton. Zooplankton data are available from the studies of Fotheringham (1977). These samples were collected at various time between May and December. The zooplankton numbers were highest in the spring and lowest in the summer. Missing data for January through April makes this comparison incomplete, however. Fotheringham found a higher proportion of meroplankton in the field than in the control area and he suggested that larvae from the fouling communities make a significant contribution to the plankton communities.

Ichthyoplankton. Ichthyoplankton samples from the Buccaneer field were characterized by a high incidence of egg and larvae (Finucane *et al.*, 1979; Finucane and Collins 1977). The highest egg (66% of total collected) and larval (59% of total collected) abundance occurred during the summer with the lowest egg and larval numbers observed in February. Anchovies (engraulids) were the most abundant and together with the gobies, bothids, carangids, and sciaenids comprised the majority of the total catch. Overall, 39 families, 59 genera, and 40 species of fish larvae were identified.

Finucane *et al.* (1979) and Finucane and Collins (1977) suggested that the study area is a spawning ground for callionymids, anguilliformes, clupeids, engraulids, scombrids, sciaenids, and soleids. They found larval species such as the little tuna (*Euthynnus alletteratus*), the scaled sardine (*Harengula jaguana*), the thread herring (*Opisthonema aglinum*), the sardine (*Sardinella* sp.), and the silver perch (*Bairdiella chrysura*), only in the oil field. The authors suggested that the area around the oil field structures may also serve as spawning grounds for these species.

Macrocrustaceans. Workman and Jones (1979) reported collecting 39 species of macroinvertebrates in trawl samples taken in October 1977 and March 1978. In quarterly trawl collections reported by Gallaway and Martin (1980), invertebrates accounted for almost 38,000 specimens out of a total 49,481 specimens caught. Almost two thirds of the invertebrate catch was accounted for by the sugar shrimp (*Trachypenaeus similis*). Chevron shrimp (*Sicyonia clorealis*), rock shrimp (*Sicyonia breviorstris*), and mantis shrimp (*Squilla empusa*) together comprised about 26% of the invertebrate catch. Penaeid shrimp made up less than 2% of the invertebrate catch.

All shrimp species, except the penaeids, reached their greatest numbers in the spring. Few or no specimens were collected in the summer. Pink and brown shrimp numbers were highest during the fall as was the abundance of the crab, *Portunus gibbesii*.

Benthos. Approximately 82,700 individuals representing 400-420 species were collected from 54 stations (Harper 1977). Macrobenthic numbers tended to decrease between July and January (concomitant with temperature decrease) and then increased into April as the temperature increased. The seasonal diversity trend was similar to that of the population trend. A total of 26 species accounted for 74.7% of all individuals collected. Polychaetes and amphipods were the dominant macrofauna taxa, generally accounting for 85% of all organisms at most stations. The smallest meiofaunal populations occurred in October-November, followed by an increase through April. Dominant among the meiofauna were the nematodes, foraminiferans, and harpacticoid copepods.

Fouling Community. Fotheringham (1977) identified 16 algal and 101 invertebrate species that make up the fouling community on the oil field structures. The fouling community is comprised of both habitat formers and a fouling mat (Gallaway *et al.* 1979). Species included as habitat formers are the barnacle *Balanus tintinnabulum*, oysters (*Ostrea*, *Crassostrea*, and *Isognomon*) and other bivalves. *B. tintinnabulum* was reported to occupy as much as 77% of the original substrate on the BOF structures (Fotheringham 1977). The fouling mat is comprised primarily of red and green algae and hydroids at the surface, and primarily of bryozoans and sponges at the mid-water and bottom stations. Associated with the habitat and mat species are the cryptic organisms including crabs (*Menippe*, *Hexapanopeus*, *Pseudomedaeus*, and *Pilumnus*), ophiuroids (*Ophiactis*), pistol shrimp (*Synalpheus*), amphipods (*Caprella*, *Corophium*, *Elasmopus*, *Erichthonius*, *Stenothoe*, and *Jassa*), tanaids (*Tanais*) and polychaetes.

Overall, the fouling community biomass was higher during the winter than during the summer (Howard and Boland 1980). On an individual species basis, however, this was not always the case. The macroalgae, for instance, had a maximum biomass during the summer. Barnacle numbers were greatest during the winter (Gallaway *et al.* 1979).

Fish. Fish living in the BOF can be characterized as being either demersal, pelagic, or reef species (Gallaway and Martin 1980; Workman and Jones 1979). Demersal species included such fish as the shoal flounder (*Syacium gunteri*), dwarf sand perch (*Diplectrum bivitatum*), sea catfish (*Arius felis*), and longspine porgy (*Stenotomus caprinus*). The latter investigators identified a total of 38 species of fish in this group. These species were present in the BOF primarily during the fall season and feed on bottom species such as crabs, shrimp, and polychaetes (Gallaway and Martin 1980).

The most abundant pelagic fish observed around the platforms was the spadefish (*Chaetodipterus faber*) although the bluefish (*Pomatomus saltatris*) was occasionally abundant (Gallaway and Martin 1980). Spadefish and the bluefish were generally most abundant in the BOF during the fall and winter. Examples of other pelagic species which were collected in the BOF included mackerel, dolphin, cobia, jacks, and sharks. Many of these fish occupy the highest trophic levels.

The abundance of the spadefish makes it one of the most important contributors to the total biomass of the BOF. This fish is primarily a plankton feeder but an analysis of stomach contents indicated that this fish also utilized the biofouling community as a food source when plankton populations were low (Gallaway and Martin 1980).

Among the most common reef fishes collected in the BOF were the red snapper (*Lutjanus campechanus*), sheepshead (*Archosargus probatocephalus*), and crested blennies (*Hypleurochelius geminatus*). The red snapper lives primarily near the bottom and feeds primarily on various shrimps and crabs. During the winter the fish may be the major food source (Gallaway and Martin 1980). This species is economically important due to its contribution to the recreational fisheries in the area. Populations of this species around the BOF were high during the fall but were radically decreased in the winter, probably because of fishing pressure (Gallaway and Martin 1980).

Sheepshead are the dominant grazers on the fouling community (Gallaway and Martin 1980). These authors observed that the BOF was a spawning site for this species as large numbers of sheepshead moved into the area in April but were gone by early May. Populations during the rest of the year were relatively uniform. Other species found in the BOF which graze on the fouling community include triggerfish, butterfly fish, angelfish, and chubs.

The crested blenny , a member of the cryptic fauna, lives in the shells of dead barnacles. This species feeds almost entirely on the fouling community (Gallaway and Martin 1980).

MODEL CONSTRUCTION

Due to recent developments in the field of systems ecology, the direction taken by this work unit has changed somewhat since initiation of the effort. When this project began in 1978, one was obliged by the state-of-the-art to develop a simulation model that matched available sampling data as closely as possible and then to determine a system behavior by varying parameters within the model and observing variations in the output. Stated another way, the direct use of most models has been to produce time series or steady state solutions for the state variables in the model. Model validity was then evaluated by comparison of model predictions with real world observations. The current trend, however, is to use an ecosystems model as the basis for analyzing and interpreting ecological structure and function (Patten 1978; Patten and Finn 1979; Patten _et al._ 1976). The basic approach uses flow analysis (Finn 1976) to investigate the fate of material passing into and through the system. Barber (1978) has presented another approach to this same problem. Matis and Patten (1981) have developed a more sophisticated form of flow analysis in which the within-system environment of each system component is partitioned into components associated with particular system inputs and outputs.

The model that is discussed in this paper uses this approach wherein model parameters are estimated from sampling data and then these estimates are used to analyze system structure and behavior by the techniques of Matis and Patten (1981).

The overall BOF model is comprised of a physical hydrodynamics component, a chemical component, and a biological system component. All of these components are coupled to produce the overall model. The objective of the hydrodynamic model is to describe the current and water movement dynamics in the BOF and to relate these movements to chemical and biological distributions. The chemical model describes the fate of oil that is introduced into the system as it is affected by various physical and biological factors. The biological systems model describes the trophic dynamic relationships that exist in the BOF.

The Biological Submodel

The first step in the construction of the model was the development of a conceptual model of the BOF. A conceptual model can be either a set of verbal statements or box and arrow diagrams that present our conception of the structure and function of the system. The conceptual design of the BOF biological system consists of ten compartments (Fig. 1). Our conceptual design differs from that of the LGL model for the BOF (Gallaway and Margraf 1978) in that we have placed the phytoplankton into a separate compartment rather than combining them in with the holoplankton.

A conceptual model makes no attempt to translate concepts into mathematics. The conceptual model has optimum accessibility and scope but little resolution. Dave Bella of Oregon State University in an unpublished manuscript defines these characteristics:

1. <u>Accessibility</u> is the degree to which a model is readily understandable to any potential user with a reasonable investment of effort. Accessibility is the extent to which the assumptions and systematic structure of a model can be critically examined and discussed. Accessibility is the degree to which a model can be applied, interpreted, and criticized on the basis of a sound understanding rather than on blind faith. A model of high accessibility thus exposes itself to inspection and critical review. In contrast, a model of low accessibility tends to protect itself from critical inspection and review.

2. <u>Scope</u> is the degree to which a model takes a broad view of environmental systems, issues, and problems. Scope describes the extent to which a model is "holistic." Broad scope implies that a model tends to encompass whole systems while a narrow scope implies a focus upon specific parts.

3. Resolution is the degree to which a model can make distinguishable the individual parts, components, and relationships. Resolution describes the degree to which a model can be specific. High resolution implies that a model includes specific descriptions and yields specific results usually with a high degree of detail and precision. A low degree of resolution implies a fairly crude ability to distinguish detail.

The whole purpose of the conceptual model is to provide accessibility and scope. Accessibility is lost in proceeding to the mathematic quantitative models because of unavoidable increased complexity. Scope is lost in proceeding to the mathematical models because of the inability to define all of the concepts by means of mathematical formulae.

Adjacency matrices and Forrester diagrams are developed as an aid to conceptual model presentation. The overall effect is to define each state variable (compartment) input and output in the model as well as the processes that control or influence inputs and outputs of each compartment.

The adjacency matrix is a convenient way to define interactions between compartments. Each filled element in the matrix represents an oriented interaction (usually energy or material flow) from row to column compartment. In a box and arrow diagram, this corresponds to

Row Compartment → Column Compartment

Each filled element contains symbols that represent the nature of the interaction, e.g., primary production, immigration, predation, etc. (Fig. 2).

System interactions displayed in the adjacency matrix are controlled or influenced by variables such as light, temperature, or biotic density. The effects of these variables are conveniently displayed in Forrester diagrams. A complete set of these Forrester diagrams for each compartment in the model are presented in Appendix A.

The Forrester diagram is the embodiment of the first stage of model development. The second stage is to develop a quantitative static model. In so doing, the data base developed in other elements of the BOF environmental program is used to construct an annual carbon flow budget based on the Forrester diagram. The actual method for translation to mathematical formulae and the manner in which other task data is used are discussed in the following section.

The static model describes system behavior over some limited period of time, in this case, one year. The quantitative dynamic model is capable of describing temporal changes in the behavior of the system by incorporating time-varying control functions instead of time averaged functions. A dynamic environs analysis is applied to this form of the model.

Mathematical Formulation

In matrix notation, the model may be represented as

$$DX = KX - LX + E \tag{1}$$

The matrix

$$X = \begin{bmatrix} X_1(t) \\ X_2(t) \\ \cdot \\ \cdot \\ \cdot \\ X_n(t) \end{bmatrix} \tag{2}$$

is the matrix of state variables, in this case the biomass in kg C/m^2 of each compartment at time t. D represents the ordinary differential operator; therefore

$$DX = \begin{bmatrix} \frac{dx_1}{dt} \\ \frac{dx_2}{dt} \\ \cdot \\ \cdot \\ \cdot \\ \frac{dx_n}{dk} \end{bmatrix} \tag{3}$$

represents the time rate of change of the independent variables (x_i). The matrix of donor-controlled transfers between compartments (expressed in units of Time^{-1}) is

$$k = \begin{bmatrix} k_{11} & k_{12} & \cdot\cdot\cdot & k_{1n} \\ k_{22} & k_{22} & \cdot\cdot\cdot & k_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ k_{n1} & k_{n2} & \cdot\cdot\cdot & k_{nn} \end{bmatrix} \tag{4}$$

where k_{ij} represents a transport to compartment "i" from compartment "j". The losses from compartments is represented by

$$L = \sum_{j=1}^{n} \begin{bmatrix} k_{ij} & & & \\ & k_{ij} & & 0 \\ & & \ddots & \\ & 0 & & k_{nj} \end{bmatrix} \tag{5}$$

The matrix E represents external gains and losses from the system (e.g., by advection, immigration, or emigration) as

$$E = \begin{bmatrix} k_{10} - k_{01} \\ k_{20} - k_{02} \\ \vdots \\ k_{no} - k_{0n} \end{bmatrix} \tag{6}$$

The ideal situation in this program would have been to estimate, from the sampling data, all of the k_{ij}. The procedure would then define the structure of the system (i.e., distinguish $k_{ij} = 0$ from $k_{ij} \neq 0$). This was not possible, however, for two reasons: (1) not enough usable data values were available and (2) primary production inputs were missing. Therefore, we were forced to make some adjustments. First, in cases where $k_{ij} = 0$, k_{ij}'s were defined a priori in order to reduce the number of parameters to be estimated to a possible number. Second, primary production was estimated by a mechanistic submodel and grazing and feeding coefficients were restricted by considering the processes as functions of required food rations. Primary production and ratio controlled formulations are discussed below.

The primary production calculations were modified from Kremer and Nixon (1978). The algorithm is followed through in logical sequence toward the ultimate aim of producing a coefficient k_{ii} in terms of time t^{-1}. The value of k_{ii} is computed for each day of the year.

From spherical trigonometry, the photoperiod (P) of the day is computed by first defining

$$\text{haversine } t = \csc p \sec d \sin \tfrac{1}{2}(p+d-h)\cos \tfrac{1}{2}(p+d+h) \tag{7}$$

where

$p = 90° -$ sun latitude

$d =$ latitude of computation point

$h =$ sun altitude (= 0 for sunrise and sunset)

sun latitude $= 23.5 \cos (2\tfrac{1}{2}(J-172)/365)$

$J =$ Julian date.

Then by setting h = 0, the local hour angle (t) of sunrise and sunset is defined as

$$t = \cos^{-1}(1\text{-}2 \text{ haversine } t) \tag{8}$$

and

$$p = 2t/15 \tag{9}$$

since the angular velocity of the earth is approximately 15°/hr.

Now, the sun angle (h) is computed at an odd number (N) of times during the day; we used N = 13 with points at sunrise, local apparent noon, and sunset. Here

$$h = \sin^{-1}(\sin p \cos d \cos t + \cos p \sin d) \tag{10}$$

Solar radiation is then computed by first considering incident solar radiation in a clear sky (I_{clear}) at sun angles h:

$$I_{clear} = S_c^{-Ta(m)m} \tag{11}$$

where

S = solar constant = 2.0 cal/cm^2-min

T = atmosphere turbidity coefficient = 0.357 (typical for coastal waters)

m = relative air mass length = $(\sin(h))^{-1}$ (atm.)

a(m) = clear sky extinction coefficient = 0.128 - 0.054 log(m) (atm^{-1})

h = sun angle (degrees).

Then actual incident radiation (I_h) is computed as

$$I_h = I_{clear}(1\text{-}R\text{+}D)(1\text{-}0.071C) \tag{12}$$

where

D = diffusive gain = $0.44\ C^{-0.22h}$

C = cloud cover in tenth, randomly chosen based on monthly mean and variance of cloud cover at Galveston

R = reflective loss = $\mathrm{EXP}(-0.149he^{-0.014h})$.

Then total radiation (I_c) for Julian date J is computed at water depth = 0:

$$I_o(\text{total}) = \int_0^P I_h\, dh \tag{13}$$

where

P = photoperiod

h = sun angle.

The limitation of primary production (R) down through the water column is based on Steele (1962)

$$R = \frac{P}{P_{max}} = \frac{I_z}{I_{opt}}\, e(1-I_o/I_{opt}) \tag{14}$$

where

P_1 = actual production (wt/time)

P_{max} = maximum production (wt/time)

I_z = $I_o e^{-hz}$

z = depth in water column

k_o = water extinction coefficient = 0.310, an average for coastal waters

k = $k_o + 0.054C^{2/3} + 0.0088C$

C = chlorophyll a concentration (mg/l)

The term $I_{opt} \geq 300$ cal/cm²-day. This is based on the average I_o (= $\bar{I}$ cal/cm²-day) that will yield I_1 (I at 1 meter depth) equivalent to I = 40 cal/cm²-day where

$$\bar{I} = I_o(1-e^{Kz})/Kz \text{ and } k = 0.50. \tag{15}$$

Computationally, $I_{opt} = 0.71_1(J-1)+0.2I_1(J-2)+0.1I_1(J-3)$ where $I_1(i)$ is I at one meter depth on Julian day i.

Finally, light limitation (R) is defined as

$$R = \int_o^z \int_o^P I(h,z)dh\, dz \tag{16}$$

where

$$I(h,z) = \frac{I_z}{I_o} e^{(1-I_z/I_{opt})} \tag{17}$$

Primary production limitation (N) by nutrients (in this case, nitrogen) is handled by simple Michaelis-Menten kinetics:

$$N = \frac{P_n}{P_{max}} = \frac{n}{K_n+n} \tag{18}$$

where

P_n = actual production

n = nitrogen concentration (μg at n/1)

k_n = half-saturation constant for nitrogen, $1 \leq K_n \leq 3$ mg at n/1.

To complete the calculations, maximum primary production (P_{max}) is computed following Eppley (1972):

$$\log \mu = 0.0275\ T - 0.070 \tag{19}$$

where

T = temperature °C

μ = specific growth rate (divisions/day)

Then

$$P_{max} = 2^{\mu} - 1 \tag{20}$$

Primary production k_{ii} is then defined as

$$k_{ii} = RNP_{max} \tag{21}$$

The formulation for primary herbivore grazing is much simpler, being based on a maximum food ratio (R_{max}) needed to maintain growth and a subsequent reduction of the maximum. Kremer and Nixon (1978) give the following formulation based on van't Hoff's Q_{10} law:

$$R_{max} = R_{maxo}e^{Q_{10}T} \tag{22}$$

where

R_{maxo} = maximum ratio at 0°C (kgC ingested/$kgC_{herbivore}$-day)
= 0.25 (Kremer and Nixon 1978)

T = Temperature °C

Q_{10} = ln 2.0/10 = 0.069(°C^{-1}).

The reduction to R_{max} based on food concentration is expressed as (Ivlev 1945)

$$0 = \frac{R}{R_{max}} = 1 - e^{-k(P-P_o)} \tag{23}$$

where

R = actual ratio

k = food availability coefficient = 7.0 (Kremer and Nixon 1978)

P = food concentration

P_o = lower feeding threshold.

Finally, the ratio is expressed as

$$R = GX_jR_{max} \tag{24}$$

where X_j = concentration of grazer (μgC/m²) and the transfer coefficient k_{ij} is computed as

$$k_{ij} = \frac{R}{P} \tag{25}$$

where P = available food concentration.

All of the other transport coefficients (k_{ij}) are estimated by use of MLAB, a comprehensive computer package that uses the Marquardt-Levenberg least squares algorithm for non-linear estimation (Marquardt 1963; Smith 1970; Knott and Reece 1973). It is well-known that non-linear least square techniques can be quite efficient given that good initial guesses of the coefficients to be estimated are available. Initial guesses at the coefficients were obtained following Bargmann (1980a) who has had success with the method essentially developed by Prony (1979) for replacing differential equations by difference equations. For the i^{th} compartment (state variable) in the model, let

$$Z_{ij} = \frac{y_i(t_{j+1}) - y_i(t_j)}{t_{j+1} - t_j} \quad ; \quad j = 1,2,\ldots,m-1 \tag{26}$$

where

m = number of observation vectors.

And let

$$x_{kj} = \frac{y_k(t_k) + y_k(t_{j+1})}{2} \tag{27}$$

and

$$Z_{ij} = \Sigma\, k_{ij_1} X_{1j} + e_{ij} \tag{28}$$

Then, using the Prony replacement, first guesses of k_{ij} can be obtained by multiple regression. When the same coefficient appears in more than one equation (i.e., where a donor has only one recipient), a simple average of the two estimates is used.

The Physical Submodel

The physical numerical model is based on the model developed by Leendertse, Alexander, and Liu (1973) and Leendertse and Liu (1975). It is based on finite difference analogues of the vertically integrated form of the equations of motion, continuity, and conservation in an incompressible fluid.

The primitive equations for incompressible flow used in the model are:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv - \frac{1}{\rho}\left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right) + \frac{1}{\rho}\frac{\partial p}{\partial x} = 0$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu - \frac{1}{\rho}\left(\frac{\partial \tau_{yz}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right) + \frac{1}{\rho}\frac{\partial p}{\partial x} = 0$$

$$\frac{\partial p}{\partial z} + \rho g = 0 \tag{29}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

$$\frac{\partial s}{\partial t} + u\frac{\partial s}{\partial x} + v\frac{\partial s}{\partial y} + w\frac{\partial s}{\partial z} - \frac{\partial}{\partial x}\left(D_x\frac{\partial s}{\partial x}\right) - \frac{\partial}{\partial y}\left(D_y\frac{\partial s}{\partial y}\right) - \frac{\partial}{\partial z}\left(K\frac{\partial s}{\partial z}\right) = 0$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} - \frac{\partial}{\partial x}\left(D_x\frac{\partial T}{\partial x}\right) - \frac{\partial}{\partial y}\left(D_y\frac{\partial T}{\partial y}\right) - \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) = 0$$

where the following definitions apply:

x,y,z	Cartesian coordinates
u,v,w	velocity components
t	time
f	coriolis parameter
p	pressure
S,T	salinity $^{\circ}/_{\circ\circ}$, temperature °C

ρ	density
K	vertical eddy diffusion coefficient
τ	components of stress tensor
D_x, D_y	horizontal eddy diffusion coefficients.

The model is arranged in levels of fixed thickness. If k-1/2 and k+1/2 are the upper and lower boundaries respectively of a level, then integrating over a level thickness yields the vertically integrated equations of motion which follow:

$$\frac{\partial(hu)}{\partial t} + u\frac{\partial(hu)}{\partial x} + v\frac{\partial(hu)}{\partial y} + (wu)_{k-\frac{1}{2}} - (wu)_{k+\frac{1}{2}} - fhv + \frac{h}{\rho}\frac{\partial p}{\partial x}$$

$$+ \left(\frac{\tau_{xz}}{\rho}\right)_{k+\frac{1}{2}} - \left(\frac{\tau_{xz}}{\rho}\right)_{k-\frac{1}{2}} - \frac{1}{\rho}\ \frac{(A_x\frac{\partial u}{\partial x})}{\partial x}\quad \frac{1}{\rho}\ \frac{(A_y\frac{\partial u}{\partial y})}{\partial y} = 0$$

$$\frac{\partial(hv)}{\partial t} + u\frac{\partial(hv)}{\partial x} + v\frac{\partial(hv)}{\partial y} + (wv)_{k-\frac{1}{2}} - (wv)_{k-\frac{1}{2}} + fhu + \frac{h}{\rho}\frac{\partial p}{\partial y}$$

$$+ \left(\frac{\tau_{yz}}{\rho}\right)_{k+\frac{1}{2}} - \left(\frac{\tau_{yz}}{\rho}\right)_{k-\frac{1}{2}} - \frac{1}{\rho}\ \frac{(A_x\frac{\partial v}{\partial x})}{\partial x}\quad \frac{1}{\rho}\ \frac{(A_y\frac{\partial v}{\partial y})}{\partial y} = 0 \qquad (30)$$

$$\frac{\partial(hs)}{\partial t} + u\frac{\partial(hs)}{\partial x} + v\frac{\partial(hs)}{\partial y} + (ws)_{k-\frac{1}{2}} - (ws)_{k+\frac{1}{2}} - \frac{\partial(hD_x\frac{\partial s}{\partial x})}{\partial x}$$

$$- \frac{\partial(hD_y\frac{\partial s}{\partial y})}{\partial y} + \left(K\frac{\partial s}{\partial z}\right)_{k+\frac{1}{2}} - \left(K\frac{\partial s}{\partial z}\right)_{k-\frac{1}{2}} = 0$$

$$\frac{\partial(hT)}{\partial t} + u\frac{\partial(hT)}{\partial x} + v\frac{\partial(hT)}{\partial y} + (wT)_{k-\frac{1}{2}} - (ws)_{k+\frac{1}{2}} - \frac{\partial(hD_x\frac{\partial T}{\partial x})}{\partial x}$$

$$- \frac{\partial(hD_n\frac{\partial T}{\partial y})}{\partial y} + \left(K\frac{\partial T}{\partial z}\right)_{k+\frac{1}{2}} - \left(K\frac{\partial T}{\partial z}\right)_{k-\frac{1}{2}} = 0$$

In order to compute the vertical current speeds, it is noted that

$$\frac{\partial w}{\partial z} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{31}$$

which implies that

$$\int_{k+\frac{1}{2}}^{k-\frac{1}{2}} \left(\frac{\partial w}{\partial z} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial z}\right) dz = 0 \tag{32}$$

Therefore, it can be shown that

$$w_{k-\frac{1}{2}} = w_{k+\frac{1}{2}} - \left(\frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y}\right). \tag{33}$$

The boundary stresses at the air-water interface are formulated as

$$\begin{aligned} T_x^s &= C \cdot (u_w^2 + v_w^2)^{\frac{1}{2}}\, u_w \\ T_y^s &= C \cdot (u_w^2 + v_w^2)^{\frac{1}{2}}\, v_w \end{aligned} \tag{34}$$

where C = drag coefficient, u_w = x-directed component of the wind, and v_w = y-directed component of the wind.

The boundary stress at the water-sediment interface is formulated as

$$\begin{aligned} T_x^b &= R \cdot (u^2 + v^2)^{\frac{1}{2}}\, u \\ T_y^b &= R \cdot (u^2 + v^2)^{\frac{1}{2}}\, v \end{aligned} \tag{35}$$

where R = friction coefficient, u = x-directed current speed, and v = y-directed current speed.

The vertical interfacial stress term is based on Reid (1957). The basic form is

$$\frac{Txz}{\rho} = l_o^2 \frac{\partial Q}{\partial z} \quad e^{-mRi} \frac{\partial u}{\partial x}$$

$$\frac{Tyz}{\rho} = l_o^2 \frac{\partial Q}{\partial z} \quad e^{-mRi} \frac{\partial v}{\partial y} \tag{36}$$

$$l_o = k \frac{(h-z)z}{h} \tag{37}$$

where k = 0.4 (von Karmen's constant, h = total water length, z = depth at which T is computed, $Q = (u^2+v^2)^{\frac{1}{2}}$, m = 1.5, and

$$\text{Ri (Richardson number)} = \frac{g \frac{\partial \rho}{\partial z}}{\rho (\frac{\partial u}{\partial z})^2} \tag{38}$$

The finite difference analogues which correspond to the vertically integrated equations of motion for the model grid system are

$$\overline{\delta_t(\bar{h}^x u)}^t = - \delta_x(\overline{\bar{h}^x u \quad \bar{u}^x})^x - \delta_y (\overline{\bar{h}^y \; v \; \bar{u}^y})^x - \bar{h}^x \; \delta_z(\bar{v}^z \bar{w}^x)$$

$$- f \; \bar{h}^x \; \bar{v}^{xy} - \frac{1}{\bar{\rho}^x} \quad \bar{h}^x \quad \underset{x}{\delta} \; P - (\frac{1}{\bar{\rho}^{xz}} \; \underset{-}{\Upsilon}^{xz})_{k+\frac{1}{2}} + (\frac{1}{\bar{\rho}^{xz}} \; \underset{-}{\Upsilon}^{xz})_{k-\frac{1}{2}}$$

$$\overline{\delta_t(\bar{h}^y v)}^t = - \delta_x(\overline{\bar{h}^x u \quad \bar{v}^x})^y - \delta_y (\overline{\bar{h}^y \; v \; \bar{v}^y})^y - \bar{h}^y \; \delta_z(v^{-z} w^{-y})$$

$$+ f \; \bar{h}^y \; \bar{v}^{xy} - \frac{1}{\bar{\rho}^y} \quad \bar{h}^y \quad \underset{y}{\delta} \; P - (\frac{1}{\bar{\rho}^{yz}} \; \underset{-}{\Upsilon}^{yz})_{k+\frac{1}{2}} + (\frac{1}{\bar{\rho}^{yz}} \; \underset{-}{\Upsilon}^{yz})_{k-\frac{1}{2}} \tag{39}$$

$$\overline{\delta_t(hs)}^t = - \delta_x(h^{-x} u \; s^{-x}) - \delta_y(h^{-y} v \; s^{-y}) - h^{-z} \delta_z(w \; s^{-z})$$

$$+ \delta_x(h^{-x} D_x \; \delta_x s)_- + \delta_y(h^{-y} D_y \; \delta_y s)_- + h^{-z} \delta_z(K \; \delta_z s)$$

$$\overline{\delta_t(hT)}^t = - \delta_x(h^{-x} u \; T^{-x}) - \delta_y(h^{-y} v \; T^{-y}) - h^{-z} \delta_z(w \; T^{-z})$$

$$+ \delta_x(\overline{h}^x D_x \delta_x T)_- + \delta_y(\overline{h}^y D_y \delta_y T)_- + \overline{h}^z \delta_z(K \delta_z T)$$

$$\delta_{zw} = \delta_x(\overline{h}^x u) - \delta_y(\overline{h}^y v).$$

The finite difference analogue for the water surface anomaly is

$$\overline{\delta_t \eta}^t = - \sum_k (\delta_x(\overline{h}^x u) + \delta_y(\overline{h}^y v)), \tag{40}$$

for the pressure gradient term in the top level

$$\begin{aligned} \delta_x P &= g(\overline{\rho}^x \delta_x \eta) + \tfrac{1}{2} \overline{h}^x \delta_x \rho \\ \delta_y P &= g(\overline{\rho}^y \delta_y \eta) + \tfrac{1}{2} \overline{h}^y \delta_y \rho \ , \end{aligned} \tag{41}$$

and for the pressure gradient term at deeper levels

$$\begin{aligned} \delta_z(\delta_x P) &= g\delta_x \overline{\rho}^z \\ \delta_z(\delta_y P) &= g\delta_y \overline{\rho}^z \end{aligned} \tag{42}$$

The finite difference analogues for the stress terms are:
for the surface stress

$$\begin{aligned} \frac{1}{\overline{\rho}^{xz}} \Upsilon \underline{^{xz}} &= C \, (u_w^2 + (\overline{v}^{xy})^2)^{\frac{1}{2}}_- \, u_{w-} \\ \frac{1}{\overline{\rho}^{yz}} \Upsilon \underline{^{yz}} &= C \, ((\overline{u}_w^{xy})^2 + v_w^2)^{\frac{1}{2}}_- \, v_{w-} \ , \end{aligned} \tag{43}$$

for the bottom stress

$$\begin{aligned} \frac{1}{\overline{\rho}^{xz}} \Upsilon \underline{^{xz}} &= R \, (u^2 + (\overline{v}^{xy})^2)^{\frac{1}{2}}_- \, u_- \\ \frac{1}{\overline{\rho}^{yz}} \Upsilon \underline{^{yz}} &= R \, (\overline{u}^{xz})^2 + v^2)^{\frac{1}{2}}_- \, v_- \ , \end{aligned} \tag{44}$$

and for the interfacial stresses

$$\frac{1}{\overline{\rho}^{xz}} \tau^{xz}_{-} = l_o^2 \, e^{-1.5Ri}((\delta_z u_-)^2 + (\delta_z v_-)^2)^{\frac{1}{2}} \delta_z u_-$$

$$\frac{1}{\overline{\rho}^{yz}} \tau^{yz}_{-} = l_o^2 \, e^{-1.5Ri}((\delta_z u_-)^2 + (\delta_z v_-)^2)^{\frac{1}{2}} \delta_z v_- \tag{45}$$

where

$$Ri = \frac{g\,(\delta_z \rho^-)}{\overline{\rho}^{z}\,(\delta_z u_-)^2}$$

$$Ri = \frac{g\,(\delta_z \rho^-)}{\overline{\rho}^{z}\,(\delta_z v_-)^2} \tag{46}$$

respectively.

The density is computed as

$$\rho = 1000 + \sigma_t \tag{47}$$

The boundary conditions are such that only a u, v, or w is found on a boundary. Therefore, for a closed boundary it is necessary only to set the respective variable to zero. For an open boundary in the cases considered here, the value on the boundary was specified independently of the main computations. In addition, certain terms adjacent to a closed boundary are set to zero so that no advection or diffusion of momentum, heat, or salt is allowed into the boundary. The implicit assumption is that between a closed boundary and a point adjacent to it, there are no gradients of momentum, temperature, or salinity.

The order of computation is critical in the explicit scheme used because each term must be known in order for it to take part in subsequent calculations. Assume that the computations have progressed to a time level n. At that point we have complete fields of u, v, T, S, and η at two time levels: n and n-1 where n-1 is the oldest. We also have w and p at n-1 and ρ at n and n-1. To advance the computations to the time level n+1, the computations proceed in the following order:

(1) compute w at time n based on u and v at time n,
(2) compute η at n+1 based on η at n-1 and ω at n,
(3) compute P at n based on ρ and η at n,
(4) compute u and v at n+1 based on u and v at n and n-1, p at n, and ρ at n and n-1,
(5) compute T and S at n+1 based on T, S, u, and v at n and n-1 and w at n,
(6) compute ρ at n+1 based on T and S at n+1.

The stability criterion for the momentum calculations is more severe than that for the conservative properties calculation. The criterion was taken as

$$\Delta t \leqq \min\left[\frac{\Delta x}{\sqrt{2gh}}, \frac{\Delta y}{\sqrt{2gh}}\right] \tag{48}$$

where h is the maximum depth in the water body being modeled.

The Chemistry Submodel

The hydrocarbon modeling effort involved the development of algorithms for six distinct weathering processes (evaporation, dissolution, oil-water mixing, interactions with suspended particulate matter, photo-oxidation, and microbial degradation). This model is based on a model developed by Kolpack (1977).

The state variables in the model form a matrix, one dimension of which is comprised of chemical species (i.e., aliphatics, aromatics, branched/cyclic alkanes, alkyl-substituted aromatics) and the other by class based on molecular weight. The state variables are connected to one another and to chemical classifications outside of the matrix by what are termed transfer coefficients.

These transfer coefficients are contributed to or controlled by the processes which produce time rates of change.

Diagrammatically, the system may be presented as in the following example.

Mean Molecular Weights

$$\begin{array}{lccccccccccccc}
 & 101.4 & & 130.1 & & 187.5 & & 264.5 & & 452.1 & & 681.0 & & 772.0 \\
\text{Aliphatics} & X_{11} & & X_{12} & & X_{13} & & X_{14} & & X_{15} & & X_{16} & & X_{17} \\
 & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow \\
\text{Aromatics} & X_{21} & \leftrightarrow & X_{22} & \leftrightarrow & X_{23} & \leftrightarrow & X_{24} & \leftrightarrow & X_{25} & \leftrightarrow & X_{26} & \leftrightarrow & X_{27} \\
 & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow \\
\text{Branched cyclic Alkane} & X_{31} & \leftrightarrow & X_{32} & \leftrightarrow & X_{33} & \leftrightarrow & X_{34} & \leftrightarrow & X_{35} & \leftrightarrow & X_{36} & \leftrightarrow & X_{37} \\
 & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow & & \updownarrow \\
\text{Alkyl-substituted Aromatics} & X_{41} & \leftrightarrow & X_{42} & \leftrightarrow & X_{43} & \leftrightarrow & X_{44} & \leftrightarrow & X_{45} & \leftrightarrow & X_{46} & \leftrightarrow & X_{47}
\end{array}$$

The X_i represent the state variables (in volume or mass) and the arrows represent the transfers (in units of time^{-1}). In addition, each state variable has a potential transfer out of the state matrix.

The specific formulations are as follows:

1. Evaporation

$$\frac{dX}{dt} = \frac{(5.21388 \times 10^{-6}) M_{oi} U_{ht}}{(M_{oi} + 28.966)\ P\ (\ln ht/Z_0)^2} (C_{hti} - C_{oi}) \qquad (49)$$

where

$5.21388 \times 10^{-6} = k^2 p$

k = von Karmen's constant = 0.38

28.966 = molar weight of dry air (gm/mol)

P = atmospheric pressure (mbar)

U_{ht} = average wind velocity at height ht (m/sec)

C_{ji} = vapor pressure of component i at height j (mbar)

Z_o = sea surface roughness (cm)

ht standard height (m)

M_{oi} = molecular weight of component i

2. Dissolution

$$\frac{dX}{dt} = \frac{APC_{si}D_iT\,[\,7 + 3.5\,(pH-7)]}{\ln\,(S/Z_o)^2} \tag{50}$$

where

$A = 2.17 \times 10''$ = coefficient for T, S, pH, etc.

C_{si} = solubility of component i (gm/cm^2)

$D_i = 10^{-7}$ = eddy of diffusion coefficient (m^2/sec)

T = oil temperature (°Kelvin)

S = mixed layer thickness

3. Oil-Water Mixture

$$\frac{dX}{dt} = 9.34 \times 10^{-9}\ \frac{VaVr}{V^2}\ (10.5-pH)\quad P_w\ g\pi(\frac{Hx}{Tpx}C\ \frac{2\pi z}{L^2} + \frac{Hs}{Tps}\ C\ \frac{2\pi z}{L_6^2}\quad 1.92 \tag{51}$$

where

V_a = volume of asphaltines (m^3)

V_r = volume of residuum (m^3)

V_t = total oil volume (m^3)

H_x = wave height (m)

T_{px} = wave period (sec)

H_s = tidal height (m)

T_{ps} = tide period (sec)

P_w = water density (gm/cm^3)

g = gravitational acceleration (m/sec^2)

Z = water depth (m)

L = mixing length (m)

4. Suspended Particular Matter

$$\frac{dX}{dt} = (1.4 \times 10^{-12})\ S_i\ (1\text{-}0.023\ Sal) \tag{52}$$

where

S_i = sediment load (gm/m^3)
Sal = salinity (τo)

5. Photo-oxidation

$$\frac{dX}{dt} = \frac{(1-C)\ (D \cdot 10^{-6})}{A(0.00362 + 368D)} \tag{53}$$

where

C = cloud cover (tenths)
D = oil thickness (m)
A = sun altitude (degree)

6. Microbial Degradation

$$\frac{dX}{dt} = \frac{R\ x_{max} - X(t-1)\ \ C^R\ \Delta t - k_1 C\ (T-T_o)}{X_{max}} \tag{54}$$

where

X = population size
X_{max} = $10^9\ .\Upsilon/m^3$
T = concentration of toxic HC
T_o = toxicity threshold (0.0001)
k_1 = proportionality constant (0.01)
R = $\frac{dB}{dt} - \frac{dD}{dt}$ (see below)
B = births
D = deaths

$$\frac{dB}{dt} = \frac{B(t-1)}{X(t-1)\Delta t} K_1\ C^{K_2}\ (T_o\text{-}270)FC \tag{55}$$

$$\frac{dD}{dt} = \frac{D(t-1)}{X(t-1)\Delta t} k_1\ C^{T-T_o} + \ 280-T_o\ + \frac{FC + ON(PH)}{k_3\ .\ X(t-1)} \tag{56}$$

where

T_o = oil temperature (°Kelvin)
F = oil concentration (ppm)
C = total oil preference coefficient
O = O_2 concentration (ml/l)
N = nitrate (millimoles)
P = phosphate (millimoles)
$k_2 = 2.5$
$k_3 = 9 \times 10^{-5}$.

Development of the hydrocarbon model is continuing under additional funding through the NOAA/OCSEAP program.

Ecosystem Analysis

Although compartmental models have been widely used to simulate ecosystem structure and dynamics, the analysis of these models has advanced significantly only recently with the adoption of economic input-output analysis (Leontief 1966) by system ecologists (Hannon 1973; Patten 1975; Finn 1976; Patten et al. 1976; Barber 1978). Patten (1978) defined the flow environment of compartments as input and output environs. Matis and Patten (manuscript) have developed an input-output environ analysis for linear compartment systems with stationary and static dynamics. Since this method partitions storages as well as flows and we are interested in both carbon and contaminant flows and storages, we have chosen to base our primary analysis of the BOF ecosystem on these methods.

The dynamics of the system may be defined as:

$$\frac{dX_i(t)}{dt} = \sum_{\substack{j=0 \\ i \neq j}}^{n} f_{ij}(t) - \sum_{\substack{j=0 \\ i \neq j}}^{n} f_{ji}(t) \tag{57}$$

where

$i \quad = 1,2,\ldots,n$

$t \ \varepsilon \ (t_o,T) = \tau \ X_i(t)$ = instantaneous storage of a conserved variable in

compartment i at time t

f_{ij} = instantaneous non-negative flows from compartment j to i, $i \neq j$.

The subscript 0 indicates the external environment; let $Z_i = f_{io}$ and $Y_i = f_{oi}$, then the above equation may be rewritten as

$$\frac{dX_i(t)}{dt} = Z_i(t) + \Sigma f_{ij}(t) - \Sigma f_{ij}(t) - Y_i(t) \tag{58}$$

In the nonsteady state case, two formulations of the model are possible:

$$\frac{dX_i(t,Z_k,X_k(0))}{dt} = Z_i(t)\delta_{ik} + \sum_{j=1}^{n} f_{ij}(t,Z_k,X_k(t)) \tag{59}$$

and

$$\frac{dX_i(t,Y_k,X_k(t))}{dt} = -\sum_{j=i}^{n} f_{ij}(t,Z_k,X_k(T)) - Y_i(t)\delta_{ki} \tag{60}$$

where

$i,k = 1,2,\ldots,n$

$\delta_{ik} = \delta_{ki} = 1$ if $i = k$, $= 0$ otherwise.

From this partition, Matis and Patten (manuscript) define matrix manipulations that define, for each X_i, the amount of material in compartment i at time t, that has entered the system via compartment K since time t_o. The matrix manipulations also describe the amount of material X_i in compartment i at time t_o that exits the system via compartment k in the time interval (t_o,t). These flows and storages are expressed in mass of material and as percentage of material.

RESULTS

Biological Model

Seasonal Biomass Trends

Fig. 3 shows the seasonal biomass cycles for the various biological compartments as simulated by the biological model. Basic patterns emerged that characterized the pelagic, benthic, and fouling communities.

Pelagic communities included the phytoplankton, zooplankton, plankton feeders, benthos feeders, and large predators. The fouling communities consisted of the fouling flora, fouling fauna, and fouling feeders. The particulates and bacteria compartment and the benthos compartment acted as the third element in the system. Lists of species which characterize each of these compartments is given in Table 7.

The pelagic community was characterized by a spring maximum, a summer minimum, and a secondary maximum in the fall. The fouling community, on the other hand, had only a spring maximum. The large predators, which are a part of the pelagic system, showed a pattern similar to that of the fouling community. This is likely due to emigration out of the system as well as increased fishing pressure.

The seasonal pattern in the particulate and benthic compartments was somewhat atypical of that in the other pelagic compartments in that standing crops reached a minimum during the summer but remained relatively uniform during the rest of the year. The minimum in the benthic compartment probably results from increased predation from the benthic feeders. The pattern in the particulate compartment is probably due to increased runoff from the bays in the winter and spring and stabilization of the water column due to formation of the thermocline thereby reducing resuspension of sediments in the summer (see Brooks _et al._ 1979).

The fouling fauna biomass was characterized by a rapid increase to a peak in the spring followed by a decline to a fairly stable population. Since the vast majority of this community is accounted for by barnacles, it is likely this pattern reflects barnacle spawning and settling activity. If this is indeed the case, the leveling of the population may represent a barnacle biomass that is limited by the amount of available space for settlement and growth on the platform pilings. With a limited amount of substrate available for settling and growth, the barnacles compete for space as they grow. Increases in biomass during this period are probably balanced by the loss in numbers (see Howard and Boland 1980).

Community Function

In attempting to understand how a system functions, it is important to understand the role of various organisms in cycling materials through the system. The biological model was designed to describe the flow and storage of carbon between the various compartments of the BOF.

Fig. 4 summarizes the flow of carbon in the BOF system, integrated over three month periods. Because advection through this system is orders of magnitude greater than flows between compartments, flows in the system are given as net flows. The flow analysis indicated that carbon enters the system through five compartments (phytoplankton, zooplankton, plankton feeders, fouling flora, fouling fauna) and exits the system through the other five compartments. Except for the fouling fauna, those compartments which are net importers are either primary producers or plankton communities whose presence in the system is influenced by advection. The net exporters are primarily those species whose distributions are less directly affected by currents (e.g., large predators, benthic feeders, etc.). The one exception was the particulates compartment. Increased particulates from the platforms may be a factor in this compartment being a net exporter.

Fig. 5 depicts seasonal variations in the net inputs and outputs to the BOF system. Flows into the system generally tend to be less variable than exports from the system. Whether this is a real feature of the system or an artifact due to a limited amount of data for these compartments is not known. External inputs and standing crops in the producer compartments vary seasonally yet these compartments show no net inputs or output during the year. This suggests that there is a rapid rate of production that is balanced by grazing on these compartments. This also suggests a threshold level for grazing to occur.

It was surprising that the fouling fauna compartment tended to produce a net input to the system yet the benthic compartment was a net exporter. However, it is likely that the net exports in the benthic compartment can be partially explained by fishing of these species. The net inputs by the fouling fauna in spite of heavy predation pressure indicates a large and rapid recruitment in this component of the system.

During the second quarter, the benthic feeders compartment was a net input to the system though an exporter during the rest of the year. It is possible that this pattern is in response to a migration of the benthic feeding species into the area followed by a heavy predation.

Although variable, the exporter compartments tend to show relatively similar amounts of export during each quarter. Rather large differences occur, however, during the second quarter in the particulates and large predators compartments. For the particulate compartment, this may represent an excess production of particulates by the platform communities beyond what is required to support the biomass in the system. In the large predators compartment, much of this biomass is lost to the system through migration of these fish from the BOF.

Carbon flows within the system are generally seasonally variant with the largest flows occurring during the spring. Various patterns emerged in the flows between compartments which should be mentioned.

The largest flows generally occurred in the benthic components of the system with the fouling component being intermediate and the smallest flows in the pelagic system. For the most part, the size of the flows increased with increasing trophic level in the pelagic and fouling components. The opposite trend was observed in the benthic components. Trends similar to those for the flows were observed in biomass levels in the pelagic, benthic, and fouling components. Flows between the pelagic and fouling components were less than flows within these two components of the system.

During the second quarter (Apr-Jul) no flow of materials was evident from the fouling fauna to the particulate compartment (Fig. 4). Similarly, during the last three quarters (Apr-Dec), no flows were observed from the plankton feeders to the large predators (Fig. 4). Through the whole year the major flow from the plankton feeders was to the particulate compartments.

The distinctness of the pelagic community and fouling community within the system becomes fairly evident when storages within the system are considered. Stored material refers to that carbon which is retained as biomass in the system and is not lost due to advection or respiration. Table 8 shows where material that is stored in the system originates. It can be seen that about 70% of the material that is stored in the zooplankton, plankton feeders, particulates, benthos, and benthic feeders compartments originates in the phytoplankton compartment during the first and third quarters. The percentage is slightly less during the third quarter than during the first. This percentage increases to 80% or more during the second and fourth quarters. Generally the fouling flora supplies less than 17% of the stored materials to the pelagic and benthic compartments. The reverse trend is seen in the origin of materials stored in the fouling fauna and fouling feeders compartments with the majority of the material arising from the fouling flora. However, the dependence of the fouling compartments on the fouling flora is not as marked as the dependence of the pelagic and benthic compartments on the phytoplankton. This is probably due to the dominance of barnacles in the fouling fauna compartment which, as filter feeders, will feed on the phytoplankton.

The large predator compartment showed less of a dependence on the phytoplankton than did the other pelagic and benthic components although the major portions of the stored materials did originate in the phytoplankton (Table 8). Ratios of material that originated in the phytoplankton versus fouling flora components during successive quarters was: 55%: 33%; 69%: 26%; 46%: 43%; 71%: 21%.

Of the stored material which later exited the system, at least 95% or more of the material exited through the large predators. This was true for all quarters. The fact that the material exits primarily through the large predators is not unexpected since the large predators will be feeding on the plankton feeders, benthos feeders, fouling feeders, and other large predators. The loss of the material will result through respiration and emigrations.

The final analysis of the environs analysis considered that material which flowed directly through the system without being stored. Similar results as that described for storages above were obtained in that the majority of the materials entered through the phytoplankton and fouling flora compartments and exited through the large predators.

Chemical Model

When oil enters the marine environment, it can undergo various physical, chemical and biological modifications. The processes which were considered in the Buccaneer oil field chemical model included evaporation of volatile components, sedimentation, dissolution, emulsification, photo-oxidation, and microbial degradation.

Rates were calculated for the various degradatory processes acting on the oil that enters the system (Table 9). Eight orders of magnitude difference existed between the various processes with microbial degradation being the most significant and sedimentation being the least significant. These rates tended to remain constant throughout the simulation except for the rate of emulsification which increased by two orders of magnitude over the 24 hr. simulation period.

Over the 24-hour period approximately 10% of the total hydrocarbons are lost due to weathering. During this period, 16% of the aliphatics are lost; over 99% of the aromatics; 58% of the branched/cyclic alkanes; and 4% of the alkyl substituted aromatics (Fig. 7).

Fitness of the Model

There are two major schools of thought in modern quantitative ecology: mathematical ecology and systems ecology. The former uses techniques such as discriminant analysis to define patterns in community structure; the energy dynamics of the biota is not necessarily of major concern. The latter is concerned primarily with the functioning of the biota as an integrated system. Until the introduction of those techniques which were used to develop the BOF model, practitioners of systems ecology were usually obliged to rely on mathematical ecology techniques to define patterns and relationships among the biota. These patterns and relationships were then used to define the structure and fundamental dynamics of the system. The techniques outlined in the previous section (see section on the Biological Submodel) now make it possible to incorporate valid statistical procedures into the estimation of model parameters.

To support the Marquardt-Levenbery least squares technique used for parameter estimation, mean carbon contents for each compartment in the model were estimated from all available data (these are the bold-faced numbers in each compartment in Fig. 4). These parameters were then used to support the Matis-Patten flow analysis. Due to the sparsity of applicable data and the quarterly sampling scenario, it is impossible to determine the statistical reliability of the inputs into the model. The main check we have on the validity of the data is the ability of the parameter estimation techniques to obtain convergent and relatively stable solutions (these data are presented in Appendix B). This check is, however, admittedly circular since certain aspects of the structure of the model system, such as defining identically zero transfers between compartments, are somewhat dependent on the input data. We are therefore forced to rely largely on our own judgment of the reliability of the results. We feel that, from a biological point of view and based on the behavior of the model, our flow results make a great deal of sense and are probably valid in our evaluation of the BOF system. Furthermore, the techniques used were designed to handle variability in the initial inputs. Our main concern is that large, undetected biases may exist in the input data, but we have no way of detecting these.

DISCUSSION

Community Structure and Function

One of the most significant aspects of the biological model was that it showed two somewhat unique assemblages in the BOF: one whose major inputs originated in the phytoplankton and one whose major inputs originated from the fouling flora. The different assemblages also showed different patterns of seasonal biomass.

For species such as the sheepshead which feed primarily on the fouling community, the food source provided by the platforms would be the primary reason behind their presence in the BOF. The large predators compartment recieved a proportionately higher input from the fouling community than the other members of the pelagic community. The ratio between inputs from the pelagic and fouling components varied quarterly and ranged from highly divergent to very nearly equal. This likely reflects the position of these predators at the top of the food chain and a less selective feeding behavior. This is also suggested by the fact that 95% of the stored materials exited through the large predators. This behavior allows these organisms to opportunistically feed on whatever species happens to be most abundant at the time. The seasonal nature of the flows from the fouling flora to the other components of the fouling community also demonstrates the ability of the fouling fauna to utilize other nutrient sources in the water column when macroalgal production is down.

Gallaway and Margraf (1979) constructed an earlier model of the BOF biological system which suggested that the system was particulate based. Their model suggested that the planktonic, benthic, and floral components of the system accounted for less than 12% of the total throughflow in the system. Our model, however, suggests that the system is heavily dependent on the primary producers and the particulates are a net exporter in the system.

The importance of the phytoplankton and concomitant reduced importance of the organic particulates in the system is supported by Brooks et al.'s (1980) findings that very little of the particulate organic matter in the water column is noncellular material (which would include fecal material and detritus). In most cases, cellular biomass (i.e., bacterial, phytoplankton, zooplankton) determined by ATP concentrations was greater than particulate matter determined by POC. Since ATP measuring techniques measure only living cells, it is unlikely that this particulate material was dead or decaying materials off the platform. The high levels of non-cellular organics that were observed in the spring were attributed by these same authors to fresh water inflow from Galveston Bay.

This is not to say that the particulates produced by the fouling communities are not an important part of this system. Rather, much of the particulate matter produced by the fouling community may be recycled within the community. This would be similar to the cycling of nutrients within tropical reef communities where little of the organic matter produced on the reef is lost to the surrounding waters. A second possibility is that the particulate matter produced on the platforms is rapidly carried to the bottom; at least for dead and decaying barnacles which are sloughed from the platform, this would almost certainly be the case. The model shows a large flow of materials between the particulates compartment and the benthos throughout the year (Fig. 4). Finally, advection may be such that the produced particulates are rapidly carried from the system accounting for the particulates compartment being a net exporter in the system.

The relatively large proportion of cycled material from the phytoplankton to the fouling community is probably explained by the feeding habits of the barnacles. These organisms are filter feeders and form the outside perimeter of the fouling community. If, as suggested, most of the organic materials produced by the fouling community does not get into the water column, then the barnacles must depend on the phytoplankton and zooplankton for the major portion of their nourishment. Hydrocarbon profiles of the barnacle tissues were typical of animals feeding on phytoplankton and detritus (Middleditch and West 1980).

Fate of Hydrocarbons

Various physical, chemical, and biological transformations take place when oil enters the marine environment. Both the present model and that of Smedes et al. (1980) suggest that hydrocarbons are rapidly dispersed and carried out of the BOF. However, concentration gradients for organic matter (Brooks et al. 1980), hydrocarbons, and sulfur (Middleditch and West 1980) have been observed in the sediments in the immediate vicinity of the platforms. The fact that these compounds are found in the immediate vicinity of the platform indicates that some mechanism exists to transport the hydrocarbons to the bottom in spite of the turbulence around the platform. Sedimentation does occur around the platforms (Brooks et al. 1980) so it is likely that some of the hydrocarbons are reaching the bottom through adsorption to sediments. The fact that the majority of the inorganic suspended materials are in the 2-5μM size range leaves some doubt, however, whether this could be a significant transport mechanism in view of the turbulence around the platforms. One possible mechanism of transport, however, may be through adsorption or incorporation into fecal matter. The model suggests a large transport of particulate matter (particularly from the plankton feeders) into the benthic compartment. Gallaway and Martin (1980) found that the primary food source of the spadefish (the dominant plankton feeder in the BOF) was a planktonic pteropod, Carolina longirostris. Harper (1977) found large numbers of these pteropod shells in his benthic samples. This implies a large amount of grazing by the spadefish and transport of significant quantities of fecal material to the bottom. Parker et al. (1971) calculated that the transport of oil in zooplankton fecal material could result in the deposition of significant amounts of oil on the bottom.

Sulfur is a major element in the brine discharged from the platforms (Middleditch and West 1980). It is possible that the hydrocarbons could be transported to the bottom through adsorption to these particles. Sizemore and Olsen (1980) found that sulfate reducing bacteria were especially abundant in the sediments at the platform sites. Hunt _et al._ (1973) concluded that degradation of petroleum would be extremely slow under anaerobic conditions. If these anaerobic conditions do exist in the sediments under the platforms, then this might account for the accumulation of hydrocarbons in this area.

Smedes _et al._'s (1980) model suggested that hydrocarbons could be transported as far as the coast southwest of Galveston in a matter of a few days. Middleditch _et al._ (1979b) found petroleum alkane concentrations as high as 43 ppb within 3 km of the BOF. Our chemistry model agrees with these findings as we observed only a 10% loss in total hydrocarbon levels over a 24-hr. period. These levels are also consistent with levels measured during simulated weathering experiments by Sizemore and Olsen (1980) and Sizemore _et al._ (1979).

Hydrocarbons can be accumulated by marine organisms by transfer of the pollutants across membranes or through the diet. If food chain transfer of hydrocarbons occurs in the BOF, then the flow of hydrocarbons through the system would follow the same major pathways as that described for carbon flows (i.e., the biological model). Middleditch and West's (1979) data on hydrocarbons in fish and fouling organisms seem to suggest that there is, indeed, food chain transfer of hydrocarbons in the BOF. However, there does not appear to be any biological magnification of these accumulated hydrocarbons. Data collected by Middleditch _et al._ (1979b, c, d) and Middleditch and West (1980) indicated that hydrocarbon levels in many of the compartments were generally about equal. Steady state average values for hydrocarbons in each compartment were calculated using the biological and chemical models (Table 10). In spite of the fact that hydrocarbon concentration data for system importers were available only for zooplankton and fouling fauna, model results tended to agree with the chemical data of Middleditch and his associates. However, the model results disagreed somewhat in that the calculated average steady state values were slightly higher than the actual measured values in those compartments where comparisons were possible. As such, the model shows no clear trends.

The discrepancy between the model and the measured values is not unexpected since we have no information concerning the fate of the hydrocarbons that are accumulated by the organisms. The fact that, for the most part, there are no large accumulations of hydrocarbons in the organisms would tend to suggest that most of the organisms are effectively depurating or metabolizing and excreting most of the accumulated hydrocarbons.

The model implies that the major flow of material in the BOF system arises from the phytoplankton. The large amount of advection in the BOF, however, probably means that a particular plankter's stay in the vicinity of the BOF platforms is short lived. This reduces the chances of biotransport of hydrocarbons through this pathway. The fouling communities, however, can be continually exposed to hydrocarbons released from the platforms. This would imply that the major pathway for hydrocarbon accumulations would be through the fouling community. This would account for the comparatively lower hydrocarbon levels in those species which do not feed on the fouling community as opposed to those which feed on the fouling community.

Middleditch and West (1980) found that the fouling mat beneath the platform discharge had very high levels of petroleum alkanes (122 ppm). Hydrocarbon profiles were typical of unweathered hydrocarbons which would seem to suggest that the hydrocarbons were being accumulated directly from the water. Crested blennies, which feed on the mat, also showed unweathered petroleum profiles and had a mean alkane concentration considerably higher than that of other species of fish. In contrast to these other members of the fouling community, however, the barnacles had very low petroleum alkane concentrations (2.48 ppm) and these were typical of weathered oil. Fucik et al. (1977) observed a case in Trinity Bay, Texas where bivalves placed beneath an oil separator platform accumulated significant amounts of total napthalenes over approximately three-month periods. The weathered profile of the hydrocarbons in the bivalve tissues led the authors to speculate that the resuspended sediments were the major source of the accumulated hydrocarbons even though hydrocarbons were present in the water column. Payne (personal communication, Science Applications, Inc., La Jolla, Calif.) has also observed a similar phenomenon with mussels. Whether different modes of hydrocarbon uptake do exist in the fouling organisms in the BOF is not clear at this time.

The bioassays conducted by Rose and Ward (personal communication, Energy Resource Co. Inc., Cambridge, Mass.) and Zein-Eldin and Keney (1979) indicate that very high concentrations of the brine discharged from the platforms were required to produce acute toxicities (LC 50's ranged from 9,500 ppm for larval brown shrimp to 100,000 ppm for adult brown shrimp). Rose and Ward concluded that the formation waters represent no acute hazard to plankton in the discharge plume and that potential hazards to benthic structure-associated organisms may occur only within a few meters of the outfall. Gallaway et al. (1979) stated that evidence of adverse effects due to the produced water were evident in the immediate vicinity of the discharge. However, there is no comparative data from the bioassay studies and the field studies on the levels of petroleum aromatic hydrocarbons in the tissues of exposed organisms. The lack of data for the aromatics makes it difficult to evaluate the chronic, sublethal effects of hydrocarbons in the BOF. However, based on the observations of other investigations of control, structures, and platforms with discharges, overall impacts appear to be negligible or at worst, minimal.

Trace Metals

Trace metals were not included as part of the BOF model because there was no way to convert metal concentrations into carbon equivalents. Little information is available on the dynamics of these metals in the Buccaneer field. Therefore, while there appears to be a slight contamination of the BOF organisms from these metals an accurate evaluation of the impacts that might be associated with this contamination is difficult. Some discussion is warranted, however.

The fact that Tillery (1980) observed a gradient in metals concentrations around the platforms suggests 1) inputs from the platforms, and 2) that similar mechanisms exist for transporting hydrocarbons, sulfur, and metals to the bottom. However, the produced brine was enriched only in Sr although twelve metals were identified in the brine and receiving water. Therefore, much of the metals contamination in the BOF may derive from the actual structures themselves. Anderson et al. (1979) has suggested that there is a continuous input of small metallic particles being chipped from the platform.

Anderson _et_ _al._ (1979) observed some increased metals concentrations in various organisms found in the BOF. No such pattern was seen by Tillery (1980) although this may be due to the fact that his control station was located around a well jacket. If much of the metals contamination arises from the structures in the field, as suggested above, then one would expect organisms collected from a well jacket to be equally contaminated as the organism collected from around a platform.

The seasonal variability observed in metals concentrations in the sediments suggests that environmental factors are a major influence on the distribution of metals in the BOF. These seasonal patterns were also reflected in metals concentrations of some of the organisms (Tillery 1980). Other investigators have observed similar phenomena due to both environmental conditions (Corral and Masso 1975; Fowler and Origioni 1976) and biological cycles (Betzer and Pilson 1975; Frazier 1976).

No evidence of bioaccumulation of the metals was observed in the Buccaneer field. This is not unexpected since trace elements other than mercury do not appear to consistently increase in concentration at higher trophic levels (Leland et al. 1977). Anderson et al.'s (1979) data suggested some possibility of food chain transfer from the fouling commmunity to grazers on this community. This is a result similar to that observed for hydrocarbons. However, this same pattern was not observed by Tillery (1980).

CONCLUSIONS

1. Major flow pathways in the Buccaneer system originate in two sources, the phytoplankton and the fouling flora. The major flows of materials through the zooplankton, plankton feeders, particulates (particulate organic matter), benthos, benthic feeders, and large predators originates in the phytoplankton compartment. Biomass for these compartments is highest in the spring with a secondary maximum in the fall. Major input to the fouling fauna and fouling feeders compartments originate from the fouling flora. These compartments show a biomass maximum in the spring with reduced populations the remainder of the year.

2. Particulates derived from the fouling communities do not provide a significant input to the pelagic and benthic communities around the platform. However, the particulates may be internally cycled within the platform communities providing an important food source.

3. Advection into and out of the system is orders of magnitude greater than flows between compartments.

4. Because of the large amount of advection, hydrocarbons released from the platforms are rapidly dispersed and are carried out of the BOF. However, it would appear that the released hydrocarbons can persist and be carried long distances before degradation is complete.

5. Transport of hydrocarbons into the sediments around the platforms is accomplished either through adsorption onto fecal material or attachment to sulfur particles.

6. While food chain transport of hydrocarbons may be a possibility in the BOF, there is no indication of biomagnification. Any accumulated hydrocarbons appear to be effectively metabolized and/or depurated.

7. Trace metal contaminants around the platform appear to be derived from the platforms themselves and not the discharged brine.

8. Trace metal contamination in the biota of the BOF does not appear to be a significant factor.

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Table 1. Summary of surface wind and current measurements made at various depths (m) in the Buccaneer Gas and Oil Field for 26 July to 30 August 1978 and 14 February to 20 March 1979[1].

	Jul-Aug '78	Feb-Mar '79
Wind		
Direction (from°T)	180 (S)	045 (NE)
Mean speed (m/s)	3.9	7.1
Maximum speed (m/s)	16.1	15.2
Currents (4.5 m)		
Mean speed (cm/s)	17.8	18.6
Maximum speed (cm/s)	62.0	58.0
Residual speed (cm/s)	3.0	13.5
Residual direction (towards °T)	185 (S)	250 (WSW)
Currents (10.5 m)		
Mean speed (cm/s)	12.9	15.2
Maximum speed (cm/s)	57.0	60.0
Residual speed (cm/s)	4.3	9.4
Residual direction (towards °T)	235 (SW)	250 (WSW)
Currents (18.0 meters)		
Mean speed (cm/s)	7.3	11.2
Maximum speed (cm/s)	46.0	42.0
Residual speed (cm/s)	3.4	4.4
Residual direction (towards °T)	250 (WSW)	260 (W)

[1]from Danek and Tomlinson (1980).

Table 2. Particulate organic composition in the surface (SFC) and bottom (BT) waters at Platforms 288-A (A) and 296-B (B). TSM = total suspended matter (includes organics and inorganics); POM = particulate organic matter; cellular = living particulates (i.e., phytoplankton, zooplankton, bacteria); phytoplankton = phytoplankton carbon as determined by chlorophyll concentrations which have been converted to carbon equivalents.[1]

Depth		TSM (µg/L)		POM (µg/L)		Cellular (µg/L)		Phytoplankton (µg/L)	
		A	B	A	B	A	B	A	B
Summer	SFC	288	321	141	146	310	196	14	14
	BT	530	1266	168	194	454	277	27	43
Fall	SFC	338	781	146	148	171	162	23	25
	BT	661	1015	150	162	169	189	27	27
Winter	SFC	1008	929	351	420	421	373	423	387
	BT	1075	865	362	429	445	445	423	420
Spring	SFC	814	874	337	373	299	301	90	110
	BT	1554	1740	216	238	214	310	113	126

[1]from Brooks et al. (1980)

Table 3. Mean and standard deviations of three nutrient species based on 13 stations around both Platform 288-A and 296-B in the Buccaneer field. Units are µM[a].

Season	Platform 288-A Surface	Platform 288-A Bottom	Platform 296-B Surface	Platform 296-B Bottom
Phosphate				
Summer	0.31 ± 0.03	0.32 ± 0.05	0.29 ± 0.12	0.32 ± 0.10
Fall	0.52 ± 0.05	0.55 ± 0.05	0.59 ± 0.06	0.55 ± 0.42
Winter	0.39 ± 0.02	0.40 ± 0.02	0.39 ± 0.02	0.38 ± 0.02
Spring	0.30 ± 0.05	0.36 ± 0.04	0.38 ± 0.04	0.39 ± 0.04
Nitrate				
Summer	0.31 ± 0.05	0.31 ± 0.05	0.23 ± 0.03	0.25 ± 0.02
Fall	0.38 ± 0.06	0.40 ± 0.09	0.36 ± 0.11	0.34 ± 0.04
Winter	0.34 ± 0.03	0.34 ± 0.03	0.32 ± 0.03	0.32 ± 0.03
Spring	2.73 ± 0.32	1.74 ± 0.05	3.03 ± 0.85	1.59 ± 0.20
Silicate				
Summer	2.53 ± 0.07	3.26 ± 0.52	2.00 ± 0.31	2.58 ± 0.41
Fall	5.23 ± 0.20	5.35 ± 0.16	5.04 ± 0.32	4.94 ± 0.55
Winter	1.25 ± 0.05	1.25 ± 0.05	1.15 ± 0.05	1.15 ± 0.05
Spring	4.75 ± 2.54	13.06 ± 0.35	4.57 ± 0.45	11.99 ± 2.98

[a]from Brooks et al. (1980).

Editor's Note

µM - micro-molar, equates to µ moles/l = µg-at/l

Table 4. A comparison of trace metals concentrations (ppm) in the sediments of the Buccaneer field and the BLM-South Texas OCS (BLM-STOCS). Mean concentrations (x) and the coefficient of variation (v = standard variation/x) are given. Number of samples analyzed given in parentheses after name of sample population.[a]

Element	Buccaneer Platform (4)		Buccaneer Study Control (22)		BLM-STOCS Control (6)	
	x	v	x	v	x	v
Ba	403.	(0.61)	151.	(0.80)	168.	(0.63)
Cd	1.1	(0.05)	0.8	(0.16)	0.1	(0.34)
Co	8.8	(0.13)	8.1	(0.16)	n.d.	n.d.
Cr	13.3	(0.87)	9.7	(0.17)	24.2	(0.29)
Cu	4.3	(0.08)	4.7	(0.24)	7.4	(0.23)
Fe	0.69	(0.18)	0.85	(0.25)	2.22	(0.15)
Mn	142.	(0.10)	164.	(0.22)	338.	(0.09)
Ni	14.7	(0.05)	17.3	(0.09)	20.2	(0.25)
Pb	10.4	(0.25)	9.4	(0.18)	9.0	(0.20)
Sr	60.7	(0.65)	25.1	(0.92)	n.d.	n.d.
Zn	29.6	(0.14)	29.0	(0.23)	28.8	(1.16)

[a]from Wheeler et al. (1980).

Table 5. Summary of the trace metal concentrations (ppm) in marine organisms of the Buccaneer Oil/Gas Field[a].

Sample Type	Ba	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Sr	Zn	Number of Samples in Average
						FISH						
All Fish	2.5	0.5	1.0	5.5	3.0	23.0	2.5	3.5	4.0	4.0	53.5	64
Spadefish	3.0	0.5	1.0	6.5	3.0	17.0	2.0	3.0	3.5	2.5	43.5	25
Grey Triggerfish	2.0	1.0	1.0	3.0	3.5	28.0	4.0	3.0	4.5	2.0	77.0	8
Red Snapper	1.5	0.5	0.5	3.0	2.0	19.0	1.5	1.5	4.0	2.5	49.0	8
Sheepshead	0.0	<0.5	0.0	3.5	2.5	24.0	1.5	2.0	3.0	0.5	79.0	6
Soapfish	4.5	0.5	0.0	0.0	11.0	13.0	2.0	10.0	8.0	6.5	58.0	3
						BARNACLES						
All Barnacles	57.0	18.0	3.0	2.0	17.5	157.0	15.5	16.5	9.5	124.0	230.5	32
Barnacles[1]	63.5	21.5	2.0	4.0	18.5	215.0	17.0	17.0	7.0	120.5	285.5	12
Barnacles[2]	51.5	16.0	4.0	<0.5	18.0	109.0	15.5	19.5	14.0	102.0	227.5	12

[a]from Anderson et al. (1979)
[1]exposed to produced brine from the platforms
[2]not exposed to produced brine from the platforms

Table 6. A comparison of the physiological capacity of bacteria (as a percent of the total bacterial population) in the sediments around Platform 296-B and from a control area.

Cruise	% oil degraders	% sulfur oxidizers	% sulfate reducers
Platform 296-B			
August	0	7	18
November	0	4	21
February	9	4	18
May	9	6	36
Control Site			
August	0	0	3
November	0	0	8
February	1	3	6
May	1	1	13

[a]from Sizemore and Olsen (1980).

Table 7. Some characteristic organisms of each compartment in the BOF biological model.

Compartment 1 - Phytoplankton

Compartment 2 - Zooplankton

Compartment 3 - Plankton Feeders

Spadefish - _Chaetodipterus faber_

Rough scad - _Trachurus lathami_

Spanish sardine - _Sardinella anchovia_

Scaled sardine - _Harengulae pensacolae_

Compartment 4 - Fouling Flora

green, red, and brown algae

Compartment 5 - Fouling Fauna

barnacles (primarily _Balanus tintinnabulum_), bivalves, bryozoans, hydroids, sponges, polychaetes, nematodes, amphipods

Compartment 6 - Fouling Feeders

sheepshead (_Archosargus probatocephalus_), blennies (_Hypleurochilus geminatus_ and _Blennius marmoreus_), angelfishes (Chaetodontidae), butterflyfishes (_Chaetodon ocellatus_)

Compartment 7 - Particulates and Bacteria

Compartment 8 - Benthos

polychaetes, amphipods, nematodes, foraminifera, harpacticoid copepods

Compartment 9 - Benthos Feeders

shrimp (_Penaeus_ spp., _Trachypenaeus similis_, _Sicyonia dorsalis_), shoal flounder (_Syacium gunteri_), sea catfish (_Arius felis_), red snapper (_Lutjanus campechanus_)

Compartment 10 - Large Predators

king mackerel (_Scomberomorus cavalla_), bluefish (_Pomatomus saltatrix_), little tunny (_Euthynnus alletteratus_), cobia (_Rachycentron canadum_).

Table 8. Percent (%) of carbon stored in compartment X_i that originated in the phytoplankton or fouling flora compartments. Data are integrated over three-month periods and presented for each quarter.

X_i	1 Jan-1 Apr		1 Apr-1 Jul		1 Jul-1 Oct		1 Oct-1 Jan	
	Phyto-plankton	Fouling Flora	Phyto-plankton	Fouling Flora	Phyto-plankton	Fouling Flora	Phyto-plankton	Fouling Flora
Phytoplankton	100	0	100	0	100	0	100	0
Zooplankton	77	10	89	7	75	11	86	7
Plankton Feeders	73	12	87	7	72	11	83	6
Fouling Flora	0	100	0	100	0	100	0	100
Fouling Fauna	39	54	27	71	19	77	36	60
Fouling Feeders	33	59	25	73	18	78	35	62
Particulates	70	14	81	13	68	17	80	11
Benthos	70	14	81	13	68	17	80	11
Benthic Feeders	70	14	81	13	68	17	80	11
Large Predators	55	33	69	26	46	43	71	21

Table 9. Rates in g/m^2-sec for various processes acting on oil in the BOF as calculated by the hydrocarbon model. An initial rate and a rate after 24 hrs (in parentheses) is given for the emulsification process. Rates for the other processes remained constant during the 24-hr period of the model run.

Process	Rate	
Evaporation	2.8×10^{-5}	
Dissolution	1.2×10^{-4}	
Emulsification	1.7×10^{-9}	(1.4×10^{-7})
Sedimentation	2.8×10^{-11}	
Photo-oxidation	3.9×10^{-8}	
Microbial Degradation	1.0×10^{-3}	

Table 10. Average steady state total hydrocarbon levels in each compartment of the BOF as calculated by the hydrocarbon model.

Compartment	Concentration
1	16.4
2	12.5
3	12.0
4	16.9
5	6.6
6	5.6
7	2.4
8	2.4
9	2.4
10	5.6

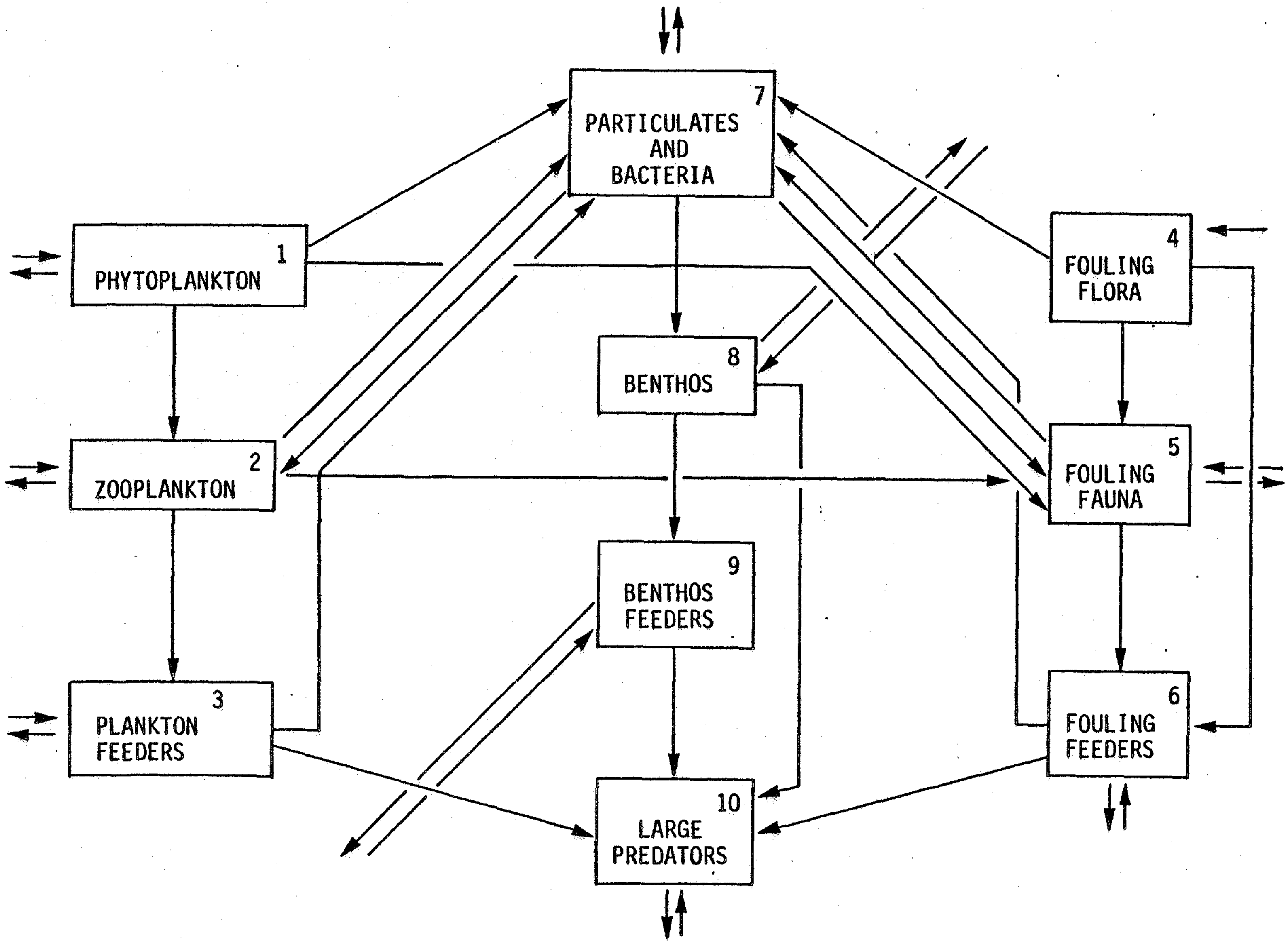

Figure 1. The conceptual model of the Buccaneer oil field biological system.

TO \ FROM	0	1	2	3	4	5	6	7	8	9	10
0		A	A	M F		M	M	A	M F	M F	M F
1	A	P									
2	A C	K									
3	M		K								
4				P							
5	M C	K	K	K	K						
6	M				K	K					
7	A C		K	K	K	K	K				
8	M C							K			
9	M								K		
10	M						K		K	K	

Figure 2. Adjacency matrix for the BOF system. A = Advection; F = fishing; K = material trophic transport; M = migration; P = primary production; an C = colonization. Compartment "O" refers to the environment external to the system.

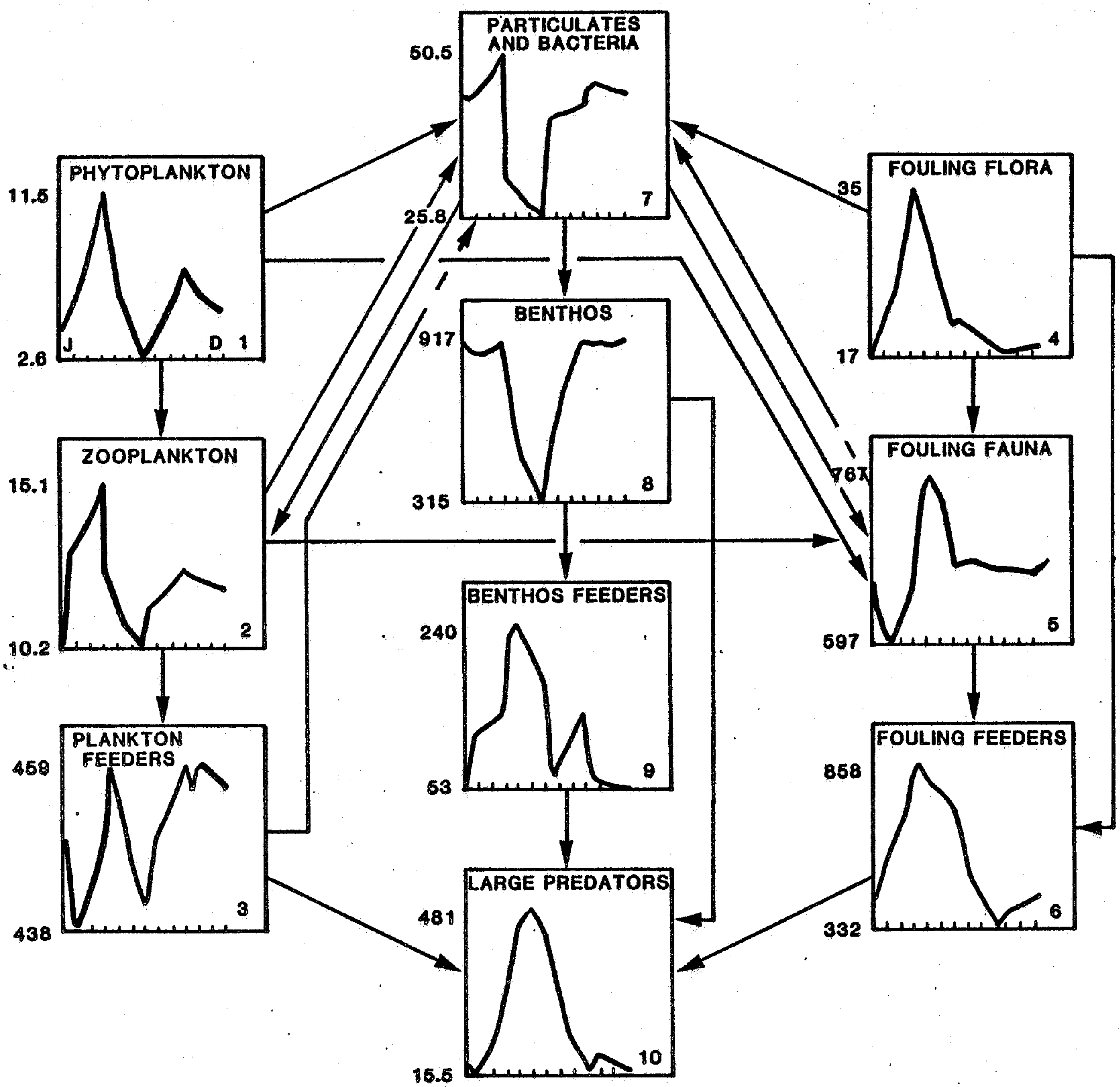

Figure 3. Seasonal biomass (gC/m²) in the various compartments of the BOF biological submodel.

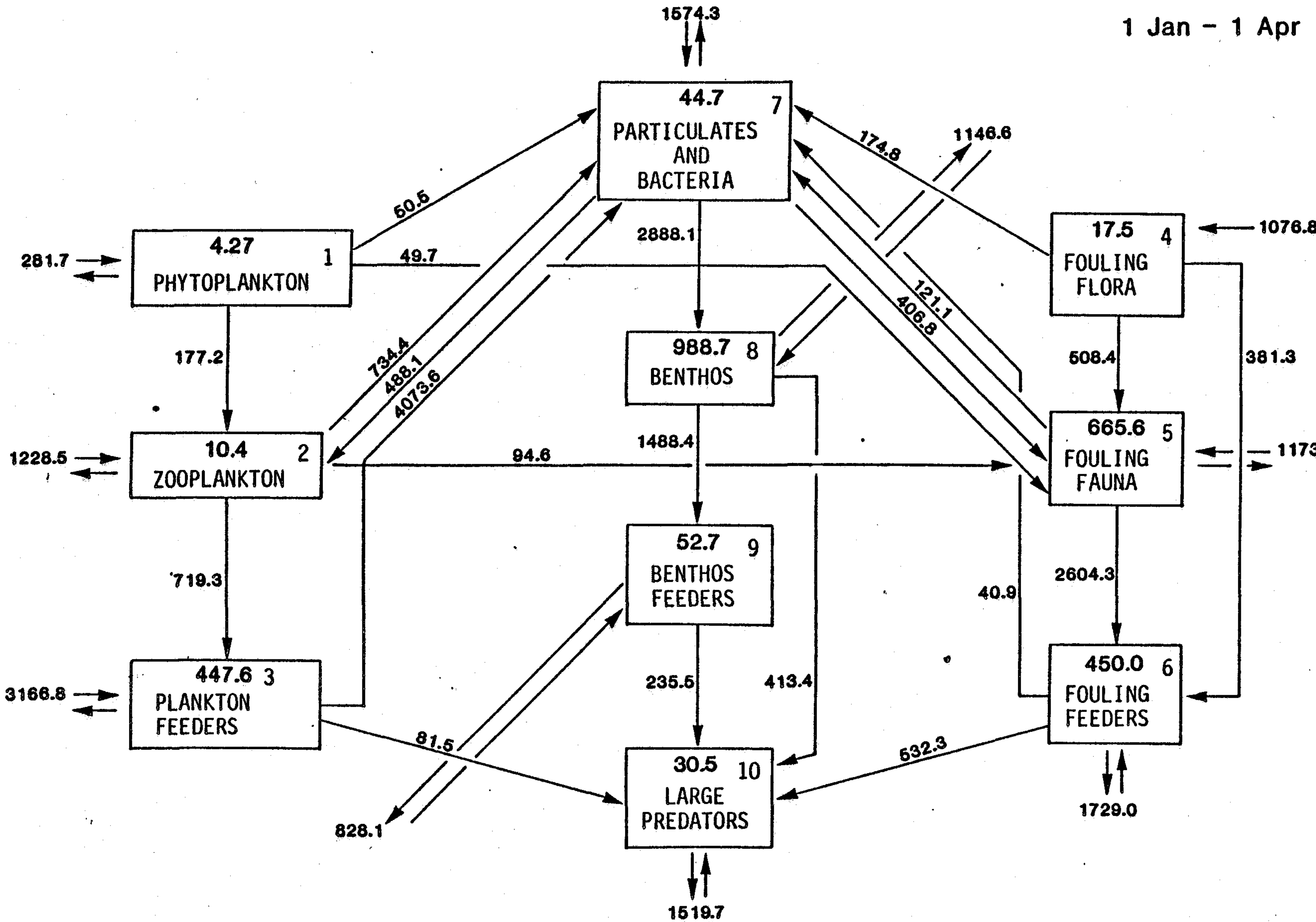

Figure 4. Quantitative carbon flows between compartments. Units are gC/m^2 integrated over 3-month periods. The model is based on a three-dimensional area around a platform that is 1 km square extending from the surface to the bottom of the water column.

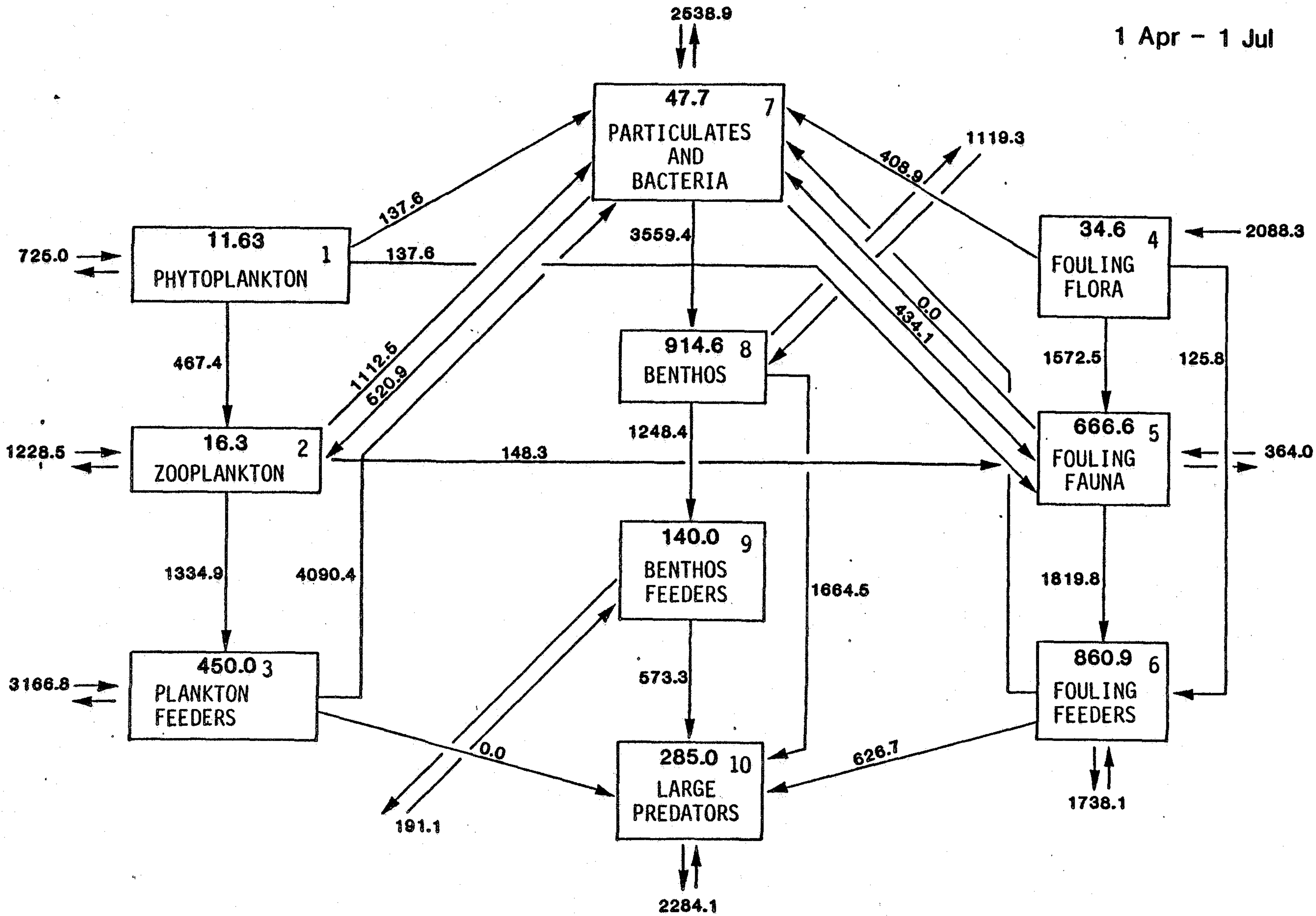

Figure 4 cont.

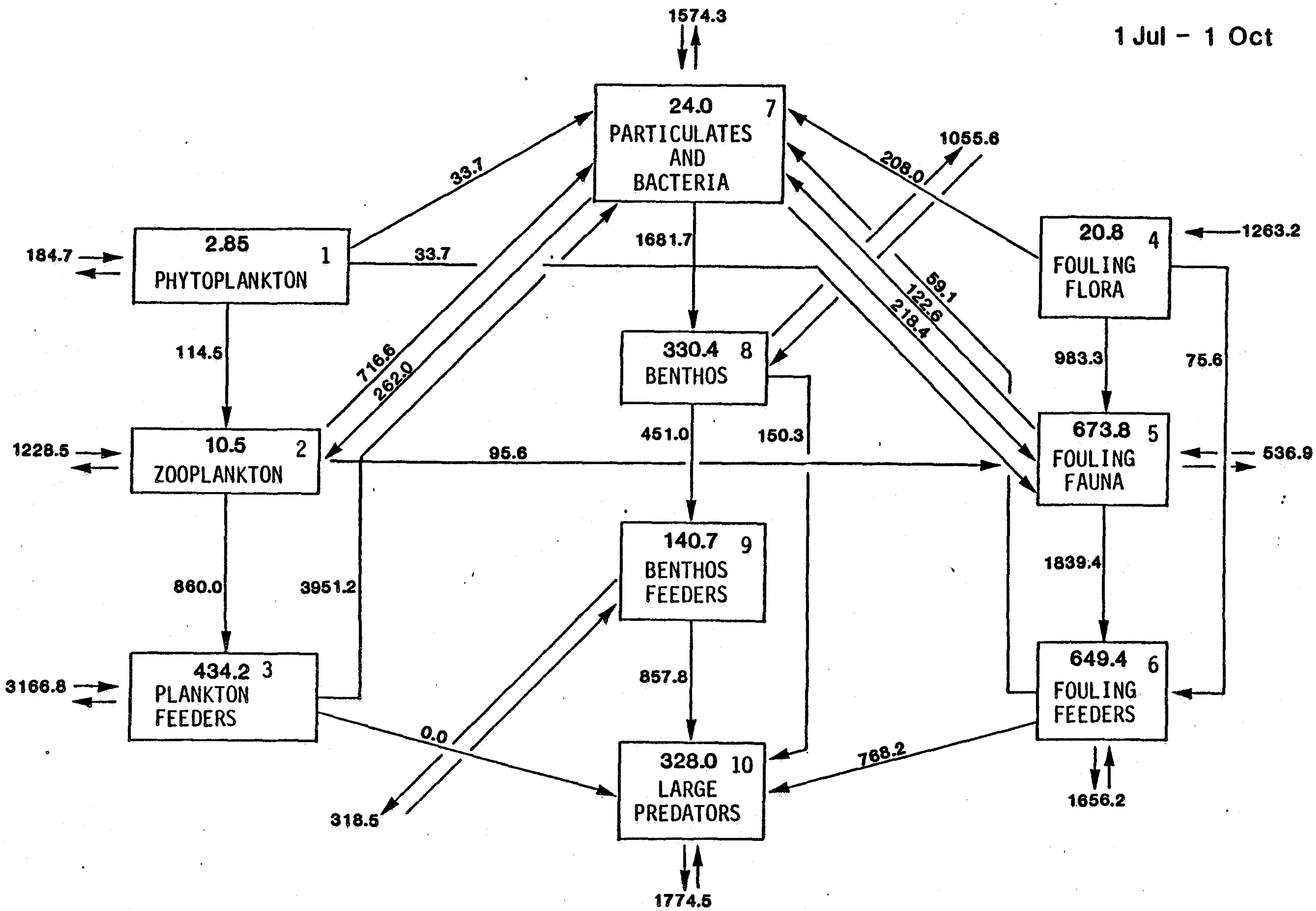

Figure 4 cont.

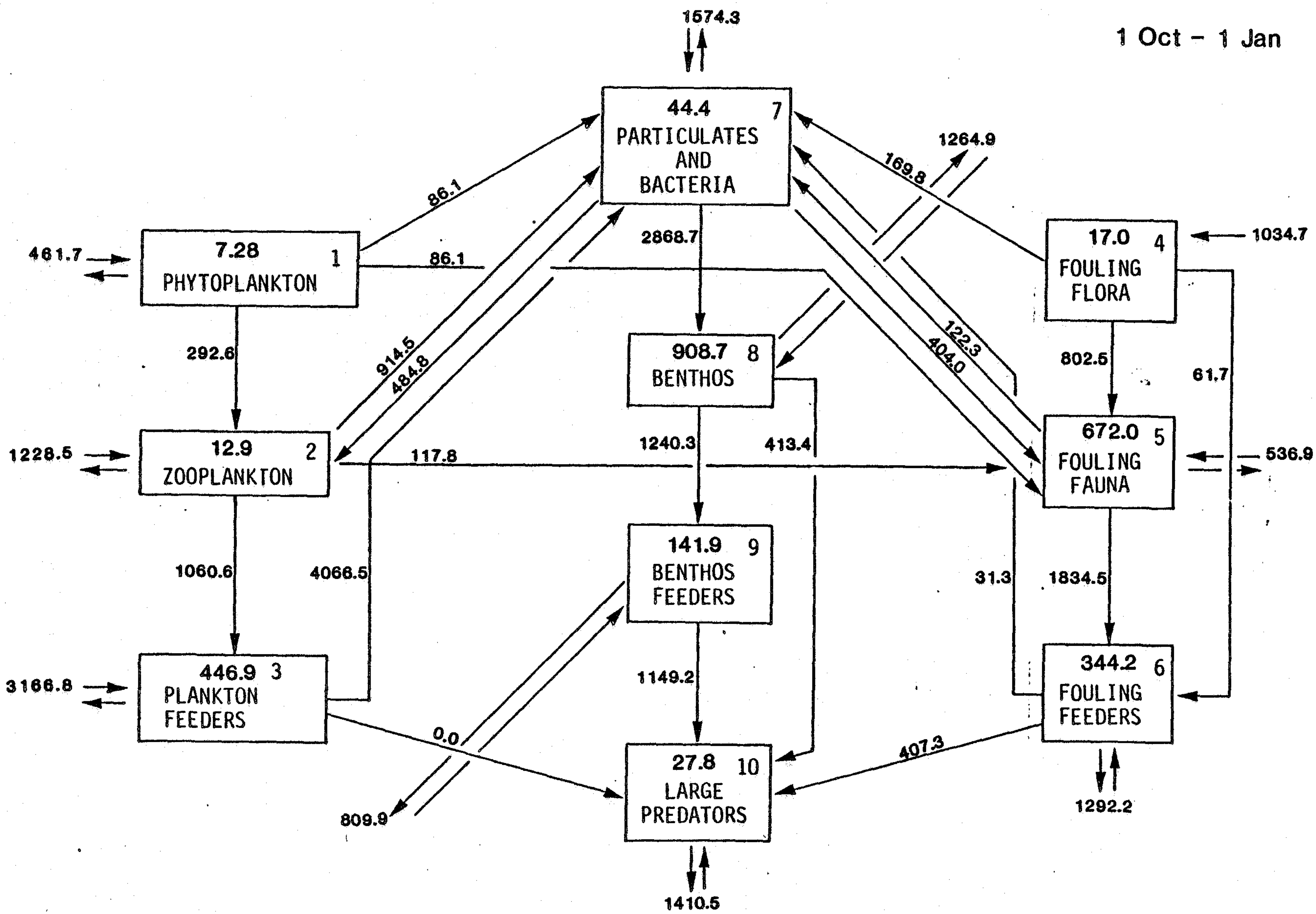

Figure 4 cont.

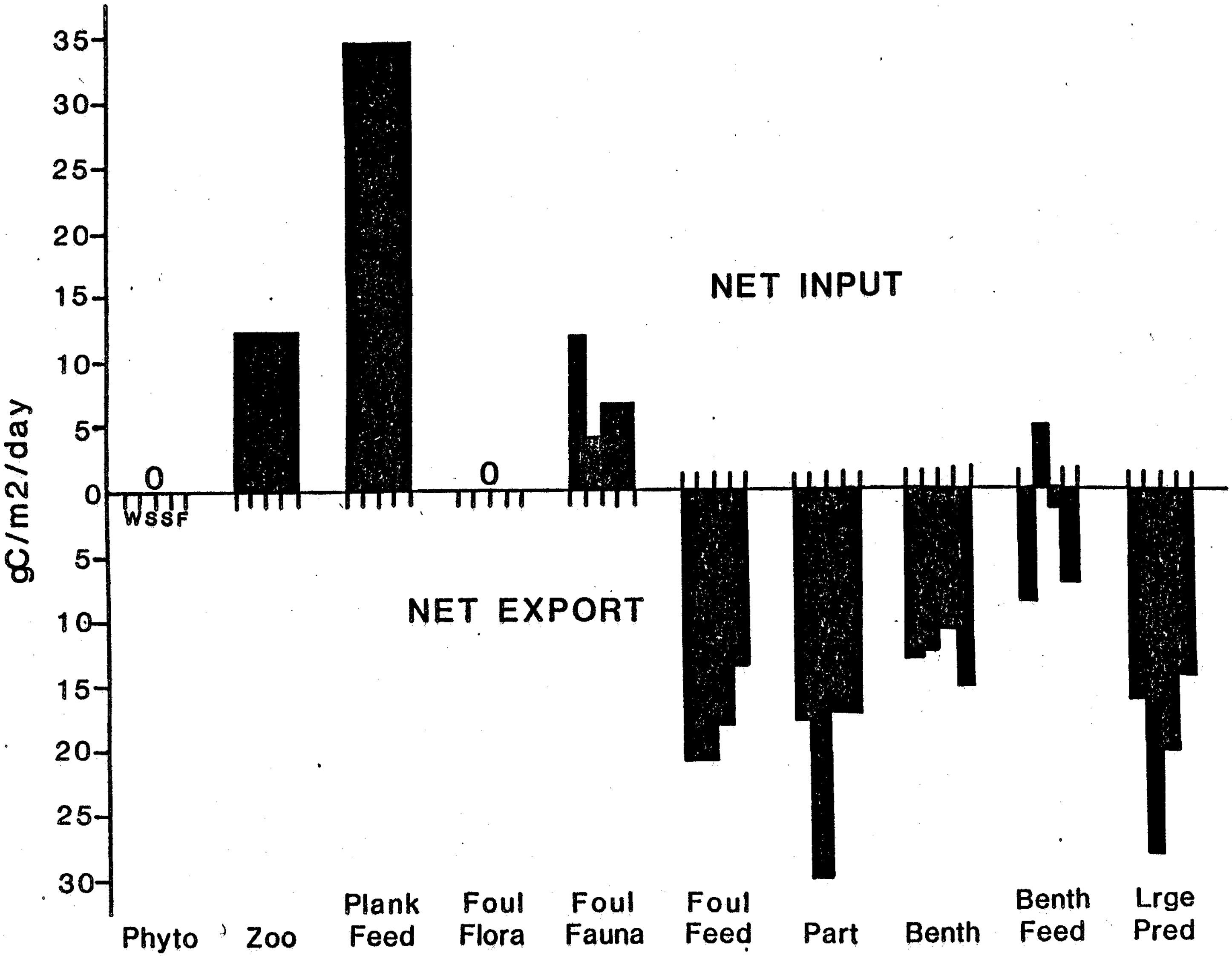

Figure 5. Seasonal variations in the net inputs and exports of carbon in the BOF system.

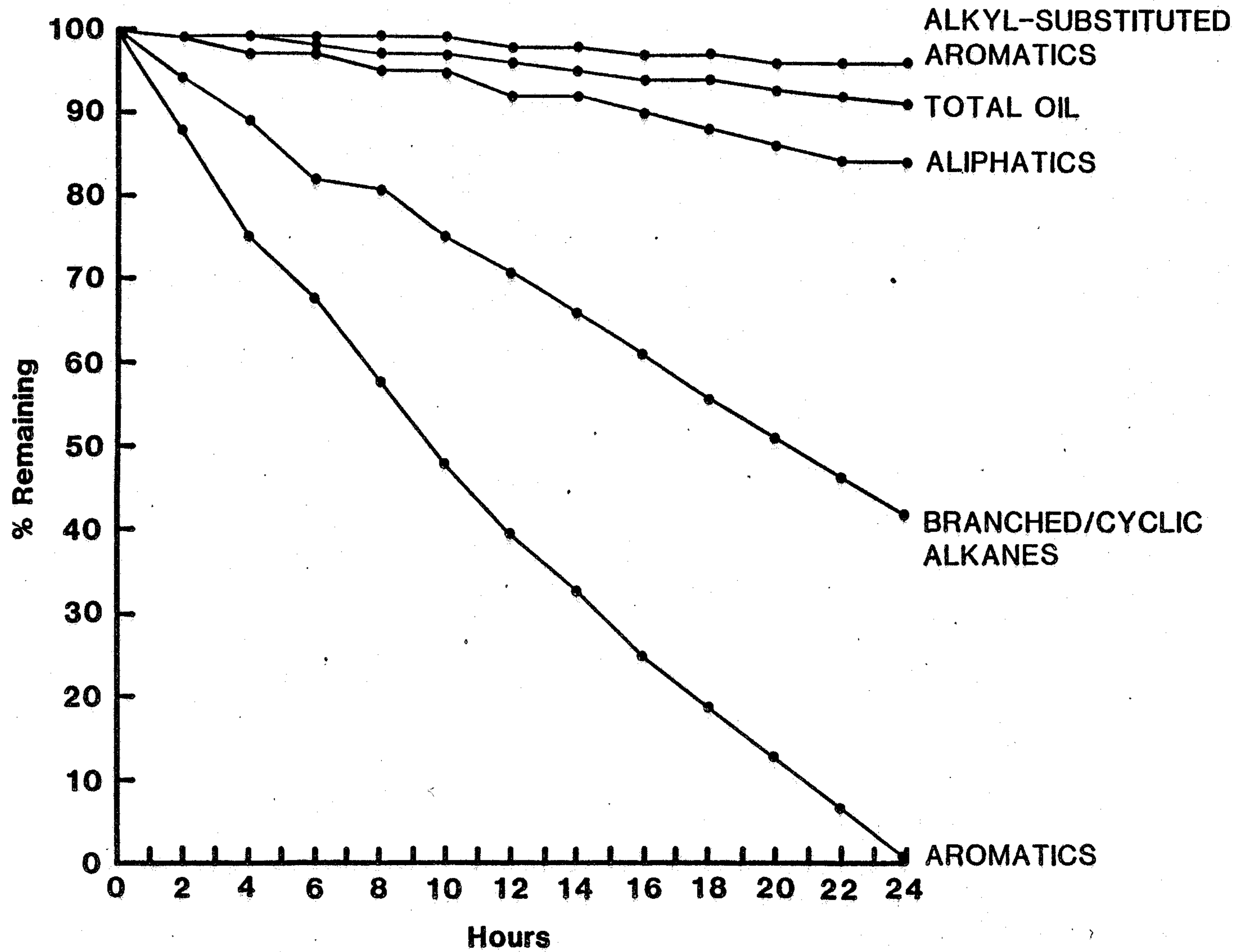

Figure 6. Model predicted loss of hydrocarbons in the BOF over a 24-hr. period.

Appendix A

Forrester diagrams for the various compartments of the BOF model

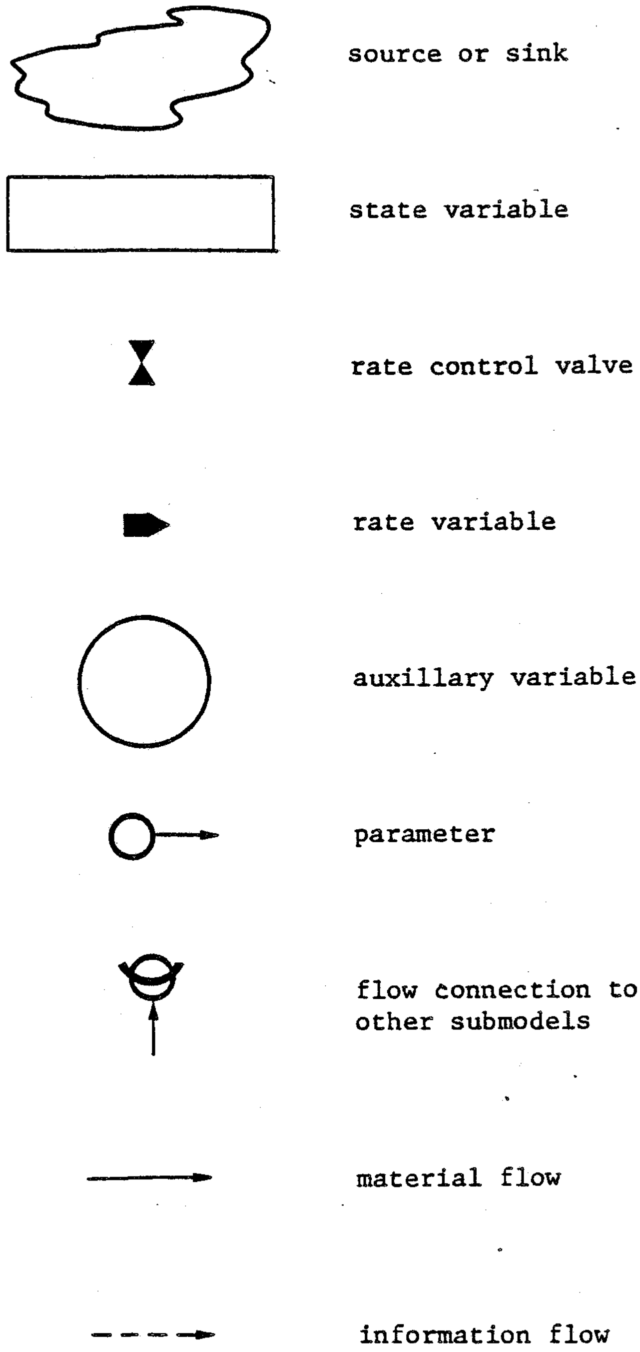

Figure A-1. Modified Forrestor symbols used in major compartment diagrams.

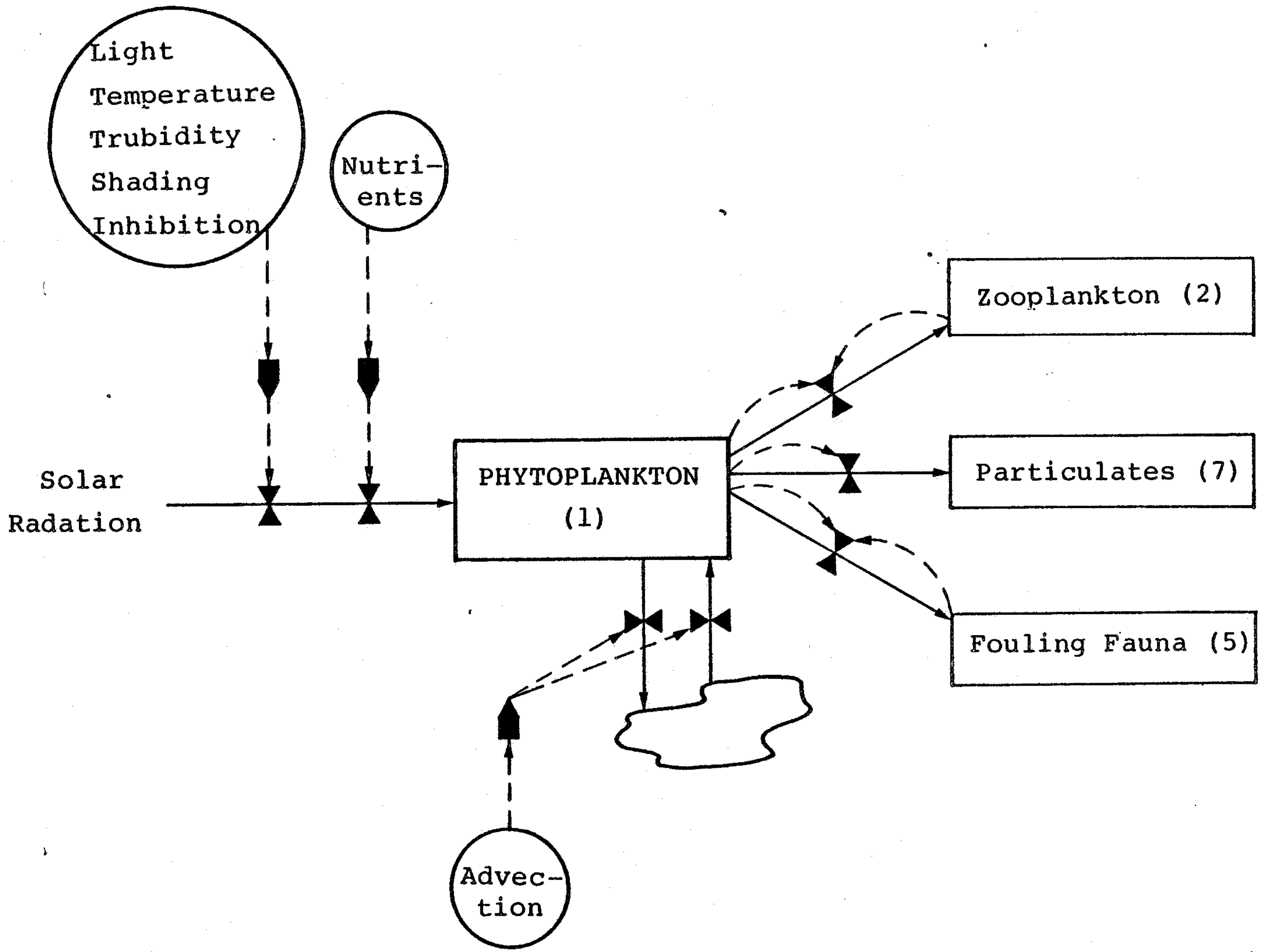

Figure A-2. Qualitative Phytoplankton model and its relation to other compartments.

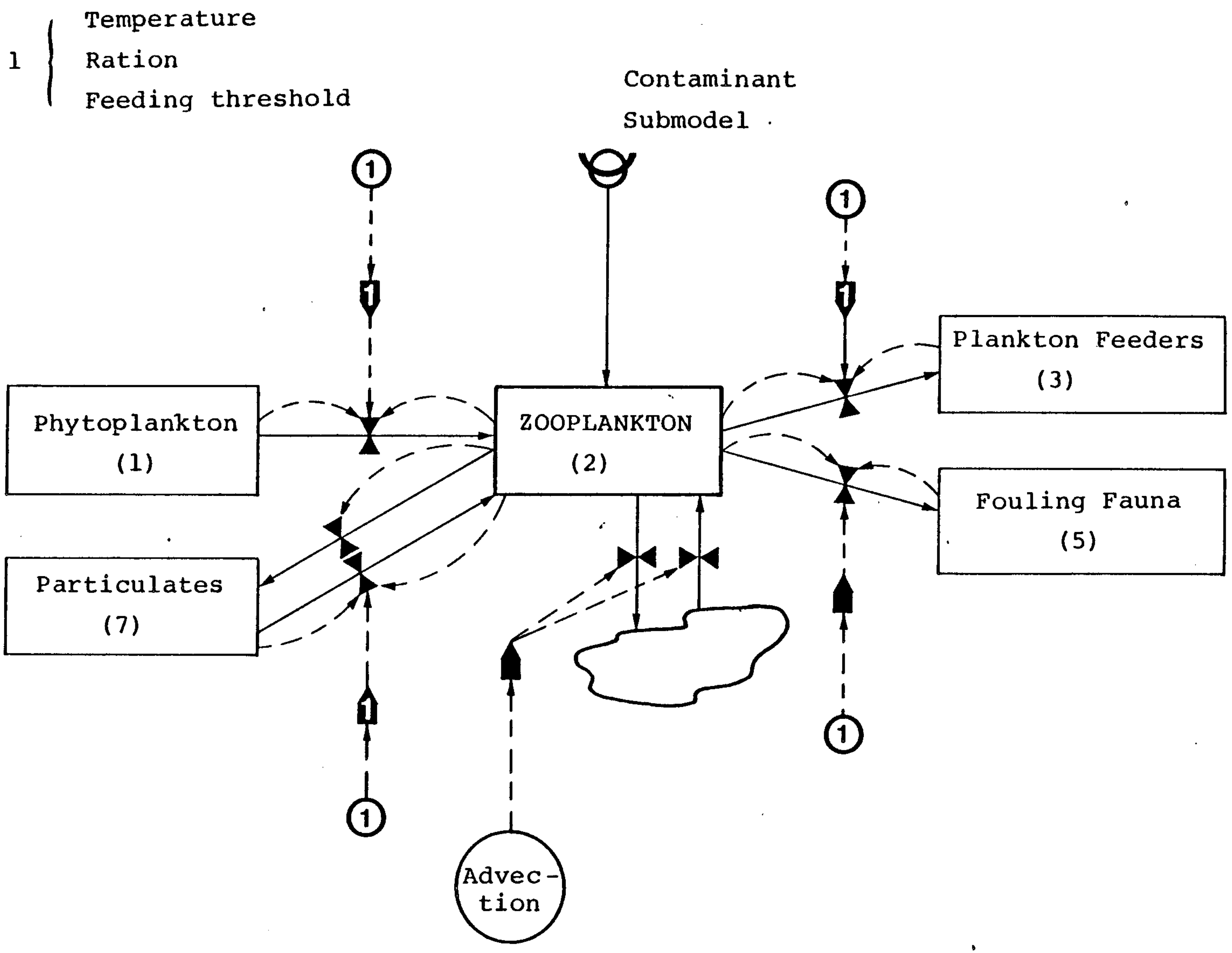

Figure A-3. Qualitative herbivorous zooplankton model and its relations to other compartments.

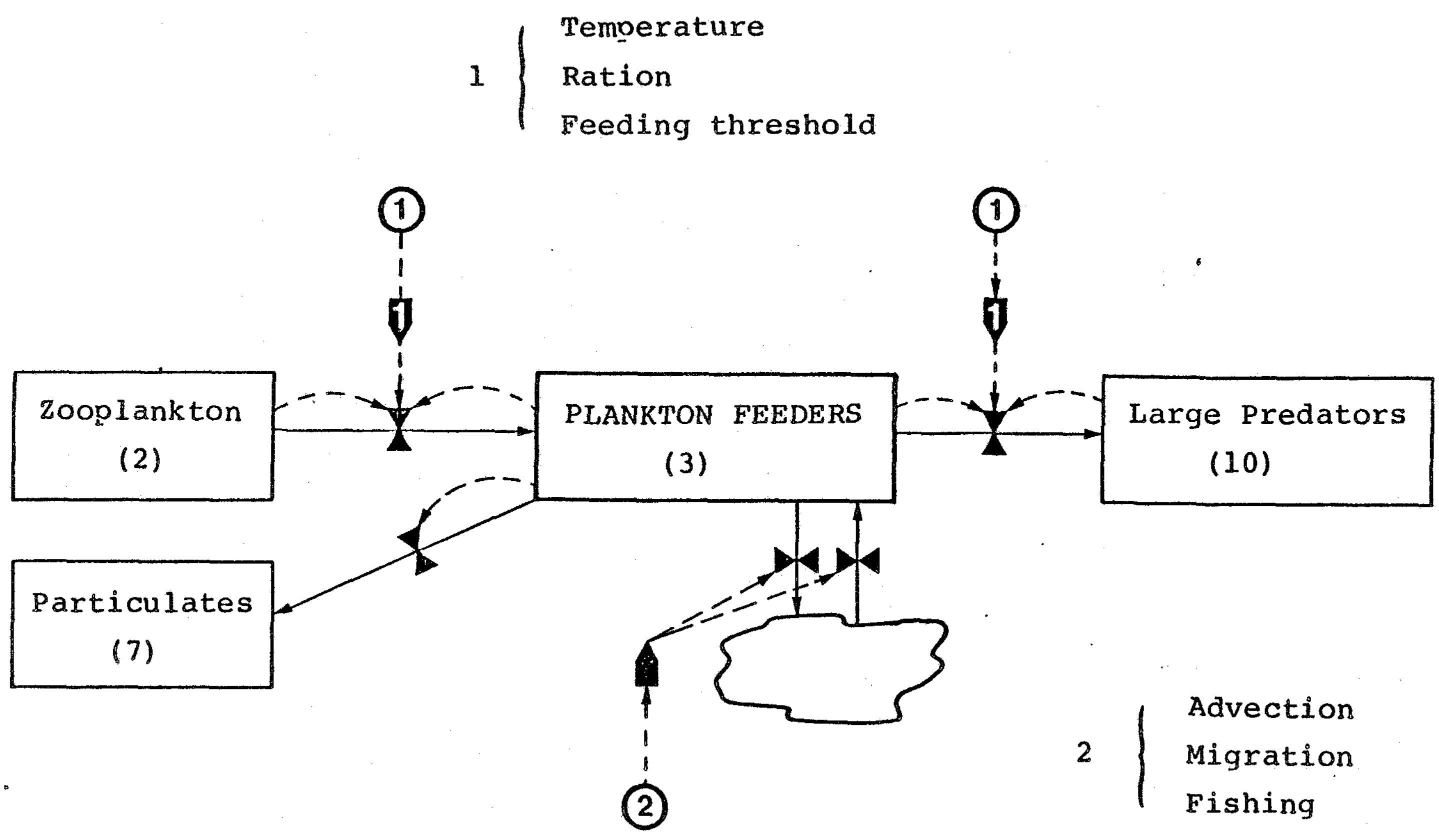

Figure A-4. Qualitative model of non-plankton feeders and carnivorous plankton and its relation to other compartments.

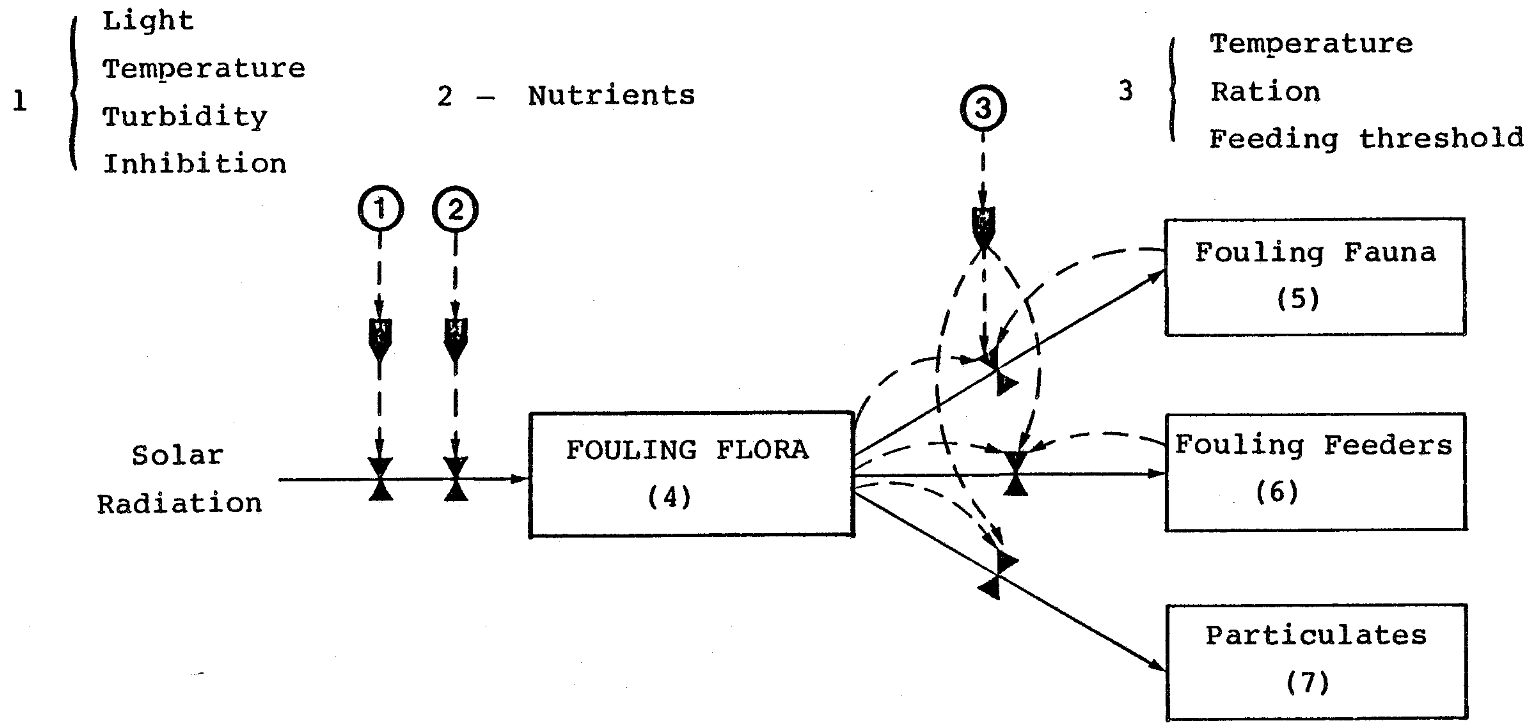

Figure A-5. Qualitative fouling model and its relation to other compartments.

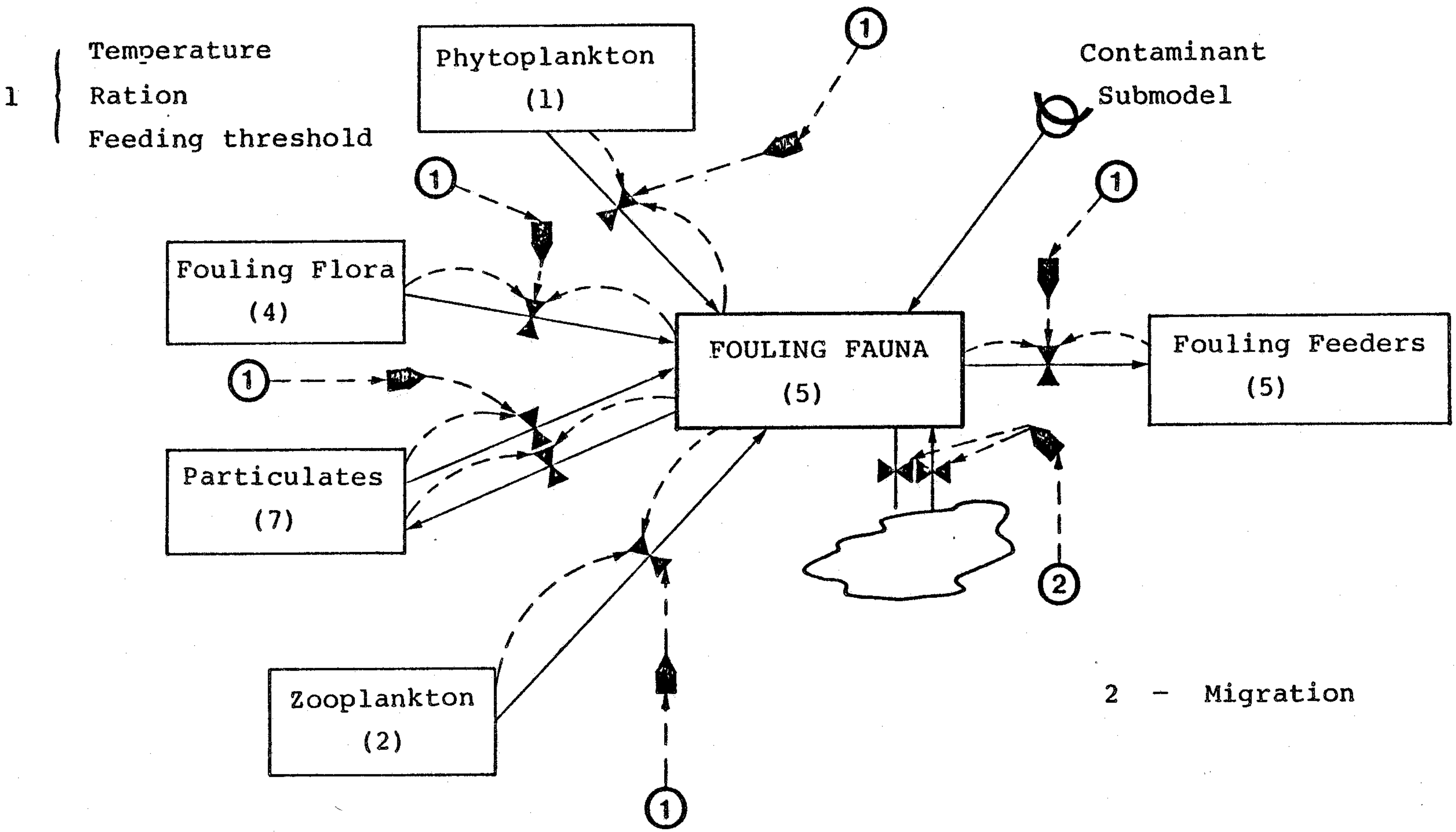

Figure A-6. Qualitative fouling fauna model and its relation to other compartments.

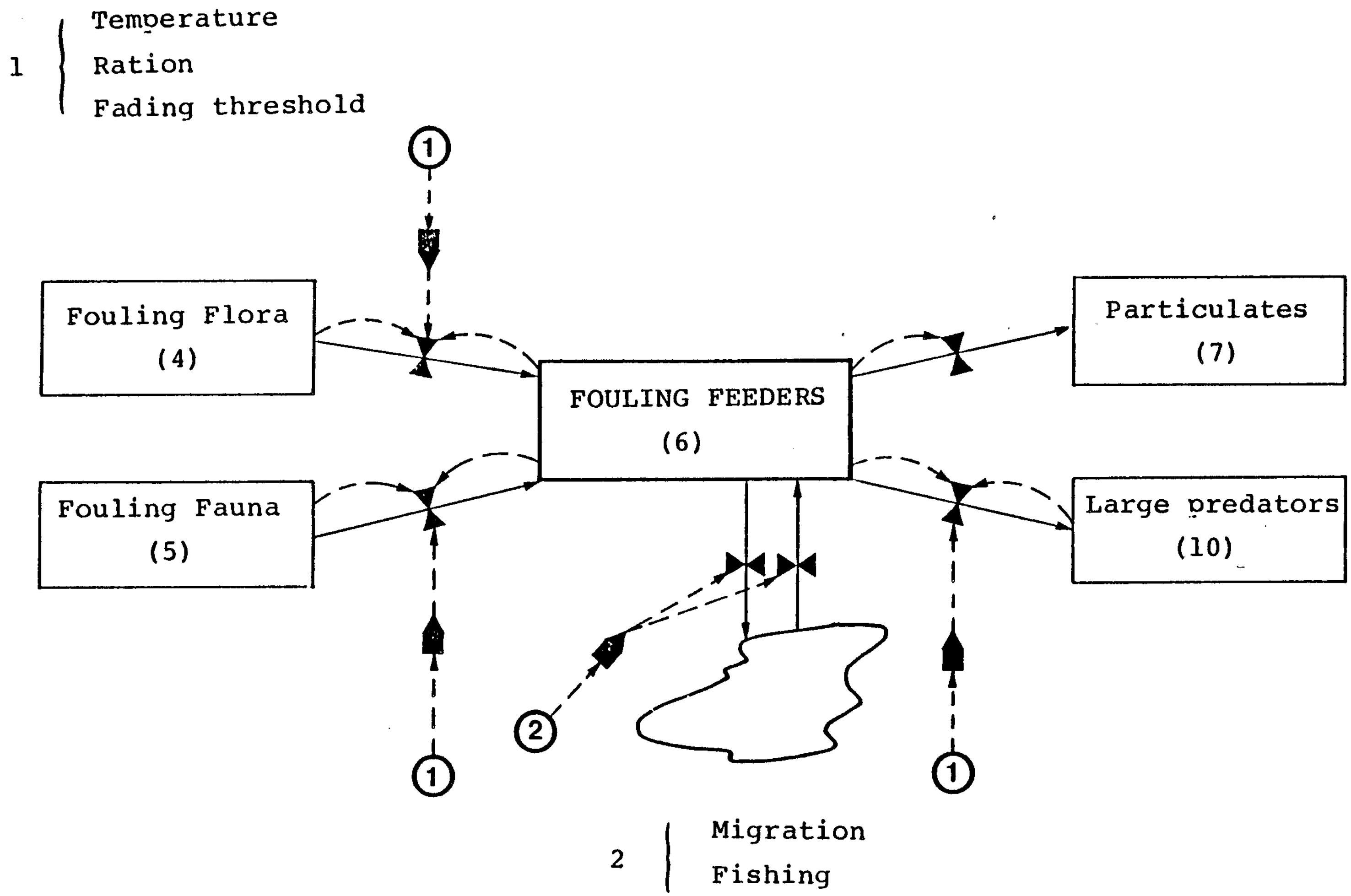

Figure A-7. Qualitative fouling Feeder model and its relation to other compartments.

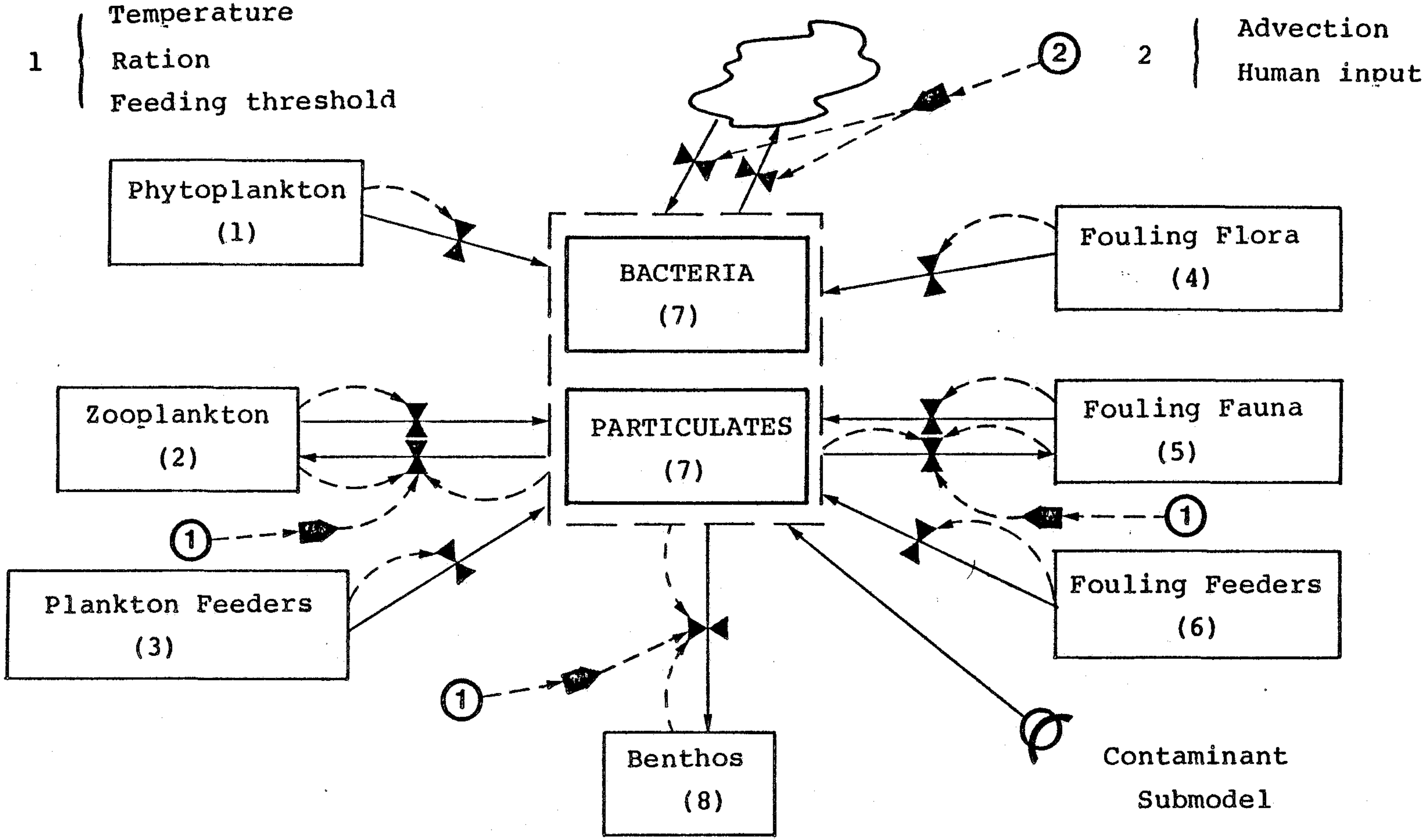

Figure A-8. Qualitative Bacteria/Particulate complex model and its relation to other compartments.

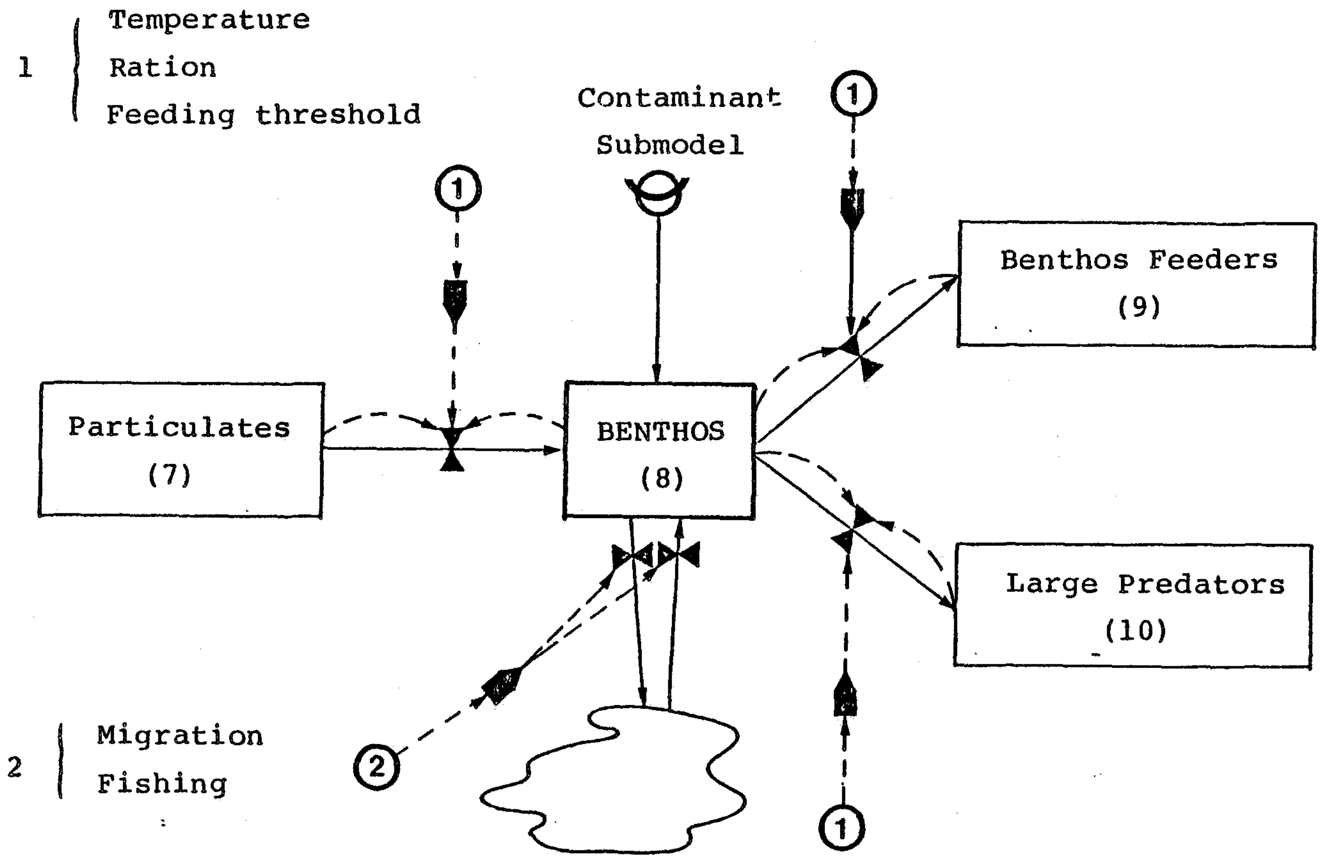

Figure A-9. Qualitative Benthos model and its relation to other compartments.

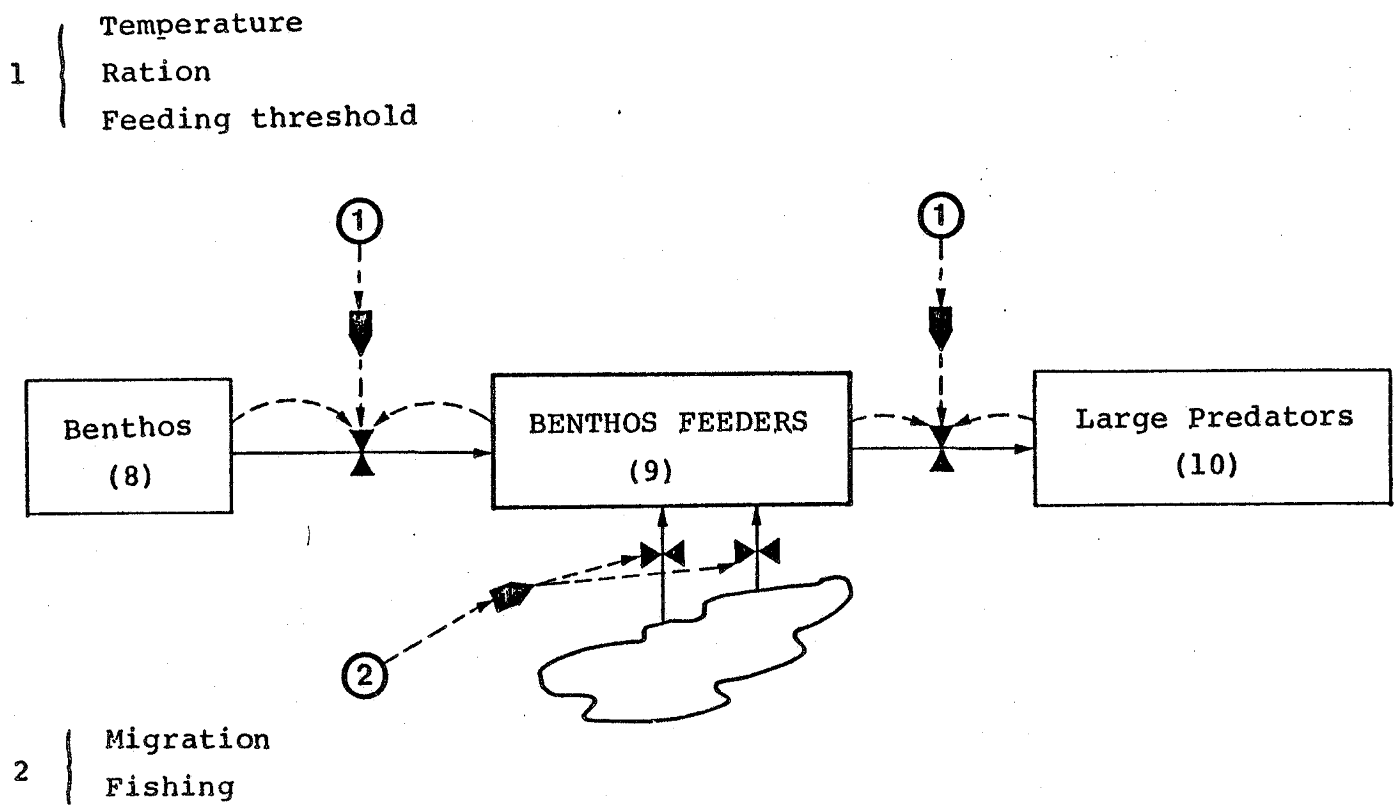

Figure A-10. Qualitative Benthos Feeders model and its relation to other compartments.

Appendix B

Model Evaluation

The solution output data is presented in the following set of tables. Overall, the data indicate that the model does an acceptable job of describing the Buccaneer system. A good indication of this can be obtained from an analysis of dependency values in the following tables. An inordinate number of values over 0.95 indicate, (1) that the model specifications are wrong (e.g., linear parameters were used where non-linear were more exact), or (2) that there is an extension of unaccountable variability in the data. While some of the dependency values approached 0.95, none actually equalled or exceeded this value. The solution output information indicates

(1) whether the solution converged to the indicated solution or whether it did not converge at the time the iterations terminated;

(2) the residual mean square,

$$\sum_{i=1}^{n} \frac{(X_{mi} - X_{ei})^2}{X_{ei}} \tag{B-1}$$

where,

X_{mi} = model prediction for compartment i based on the final solution,

X_{ei} = final value for compartment i to which model is being fit,

n = number of model compartments;

(3) sums of squares - distributed as chi-square with N-m degrees of freedom, where N = number of observations and m = number of parameters estimated;

(4) parameter dependency value - fraction of total variability in a parameter that is attributable to variations in other parameters.

$$D = \frac{1 - \text{var (parameter with others held constant)}}{\text{var (parameter)}} \tag{B-2}$$

(The highest values invariably occurred in parameters K_{51}, K_{64}, K_{98}, K_{108}, and K_{109}.)

(5) standard error -

$$SE = \frac{1}{N-1} \sum_{i=1}^{n} (X_{mi} - X_{ei})^2 \tag{B-3}$$

where N = number of data values to which the parameter is fit. The highest standard error values occurred in parameters K_{32}, K_{51}, K_{52}, K_{57}, K_{72}, K_{73}, and K_{87}.

1 JAN - 1 APR

Parameter	Final Value	Standard Error	Dependency Value
k_{11}	0.725	-	-
k_{21}	0.456	0.069	0.426
k_{27}	0.120	0.110	0.498
k_{32}	0.760	1.206	0.316
k_{44}	0.678	-	-
k_{51}	0.128	0.962	0.862
k_{52}	0.100	0.997	0.110
k_{54}	0.320	0.516	0.476
k_{57}	0.100	1.101	0.501
k_{64}	0.240	0.190	0.876
k_{65}	0.043	0.030	0.770
k_{71}	0.130	0.151	0.207
k_{72}	0.776	0.775	0.611
k_{73}	0.100	0.862	0.467
k_{74}	0.110	0.102	0.431
k_{75}	0.002	0.002	0.631
k_{76}	0.001	0.002	0.781
k_{87}	0.710	0.750	0.674
k_{98}	0.018	0.011	0.800
k_{103}	0.002	0.001	0.240
k_{106}	0.013	0.012	0.316
k_{108}	0.005	0.002	0.872
k_{109}	0.049	0.050	0.824

Solution converged

Residual mean square = 27.24

Sums of squares = 9.92

df = 17

α = 0.11 (Prob of incorrect fit)

1 APR - 1 JUL

Parameter	Final Value	Standard Error	Dependency Value
k_{11}	0.685	-	-
k_{21}	0.442	0.063	0.427
k_{27}	0.120	0.111	0.499
k_{32}	0.900	1.310	0.316
k_{44}	0.664	-	-
k_{51}	0.130	0.964	0.861
k_{52}	0.100	0.989	0.111
k_{54}	0.500	0.519	0.498
k_{57}	0.100	1.109	0.570
k_{64}	0.040	0.181	0.905
k_{65}	0.030	0.029	0.721
k_{71}	0.130	0.154	0.315
k_{72}	0.750	0.777	0.670
k_{73}	0.100	0.862	0.448
k_{74}	0.130	0.107	0.407
k_{75}	0.000	0.000	0.667
k_{87}	0.820	0.851	0.334
k_{98}	0.015	0.019	0.714
k_{106}	0.008	0.007	0.274
k_{108}	0.020	0.018	0.806
k_{109}	0.045	0.049	0.808

Solution converged

Residual mean square = 36.66

Sums of squares = 9.17

df = 17

α = 0.08

1 JUL - 1 OCT

Parameter	Final Value	Standard Error	Dependency Value
k_{11}	0.712	-	-
k_{21}	0.442	0.062	0.423
k_{27}	0.120	0.110	0.425
k_{32}	0.900	1.300	0.372
k_{44}	0.668	-	-
k_{51}	0.130	0.964	0.924
k_{52}	0.100	0.988	0.127
k_{54}	0.520	0.519	0.425
k_{57}	0.100	1.110	0.533
k_{64}	0.040	0.039	0.884
k_{65}	0.030	0.030	0.672
k_{71}	0.130	0.151	0.334
k_{72}	0.750	0.757	0.618
k_{73}	0.100	0.802	0.424
k_{74}	0.110	0.103	0.451
k_{75}	0.002	0.006	0.689
K_{76}	0.001	0.002	0.261
k_{87}	0.770	0.749	0.618
k_{98}	0.015	0.011	0.807
k_{106}	0.013	0.013	0.360
k_{108}	0.005	0.003	0.843
k_{109}	0.067	0.057	0.880

Solution converged

Residual mean square = 24.0

Sums of squares = 9.69

df = 17

α = 0.08

1 OCT - 1 JAN

Parameter	Final Value	Standard Error	Dependency Value
k_{11}	0.697	-	-
k_{21}	0.442	0.062	0.423
k_{27}	0.120	0.111	0.425
k_{32}	0.900	1.300	0.372
k_{44}	0.670	-	-
k_{51}	0.130	0.964	0.924
k_{52}	0.100	0.988	0.127
k_{54}	0.520	0.519	0.426
k_{57}	0.100	1.112	0.533
k_{64}	0.040	0.040	0.888
k_{65}	0.030	0.030	0.672
k_{71}	0.130	0.151	0.333
k_{72}	0.776	0.873	0.618
k_{73}	0.100	0.802	0.425
k_{74}	0.110	0.104	0.450
k_{75}	0.002	0.002	0.689
K_{76}	0.001	0.002	0.261
k_{87}	0.710	0.619	0.619
k_{98}	0.015	0.011	0.808
k_{103}	0.000	0.000	0.000
k_{106}	0.013	0.013	0.360
k_{108}	0.005	0.004	0.843
k_{109}	0.089	0.098	0.881

Solution converged

Residual mean square = 27.16

Sums of squares = 7.25

df = 17

α = 0.20

Appendix C

Fortran Program for the BOF Model

Part A

Central Program Module

Produces Solutions at Each Time Step

- Program Main - Controls program flow and calls subroutines.
- Subroutine Init - Zeroes and initializes arrays used in the other subroutines.
- Subroutine Input - Reads in transfer coefficients and initial state variable values.
- Subroutine Soln - Runge-Kutta technique for solution of a system of ordinary differential equations.
- Subroutine ODE - The actual system of ordinary differential equations.
- Subroutine OUT - Outputs state variables at each prescribed time step.

```
      COMMON/BLK1/AK(20,20),AL(20,20),B(20),XN(20),XNM1(20),
     .     DELT,RTS,N,NTS,IOUT
      CALL INIT
      CALL INPUT
      DO 1000 I=1,NTS
      CALL SOLN
      CALL OUT(I)
      DO 900 J=1,N
      XNM1(J)=XN(J)
  900 CONTINUE
 1000 CONTINUE
      STOP
      END
C
C
C
C
      SUBROUTINE INIT
      COMMON/BLK1/AK(20,20),AL(20,20),B(20),XN(20),XNM1(20),
     .     DELT,RTS,N,NTS,IOUT
      CALL OPEN(7,'SOFOUT  DAT',2)
      DO 100 I=1,20
      XNM1(I)=0.0
      XN(I)=0.0
      B(I)=0.0
      DO 100 J=1,20
      AK(I,J)=0.0
      AL(I,J)=0.0
  100 CONTINUE
      II=0.0
      RETURN
      END
C
C
C
C
      SUBROUTINE INPUT
      COMMON/BLK1/AK(20,20),AL(20,20),B(20),XN(20),XNM1(20),
     .     DELT,RTS,N,NTS,IOUT
      CALL OPEN(6,'SOFK    DAT',2)
      READ(6,10) N,NTS,IOUT,DELT,ADJK,RTS
   10 FORMAT(3I3,3F5.0)
      DO 100 I=1,N
      READ(6,20) (AK(I,J),J=1,N)
   20 FORMAT(1X,10F7.2)
  100 CONTINUE
      READ(6,20) (B(I),I=1,N)
      READ(6,20) (XNM1(I),I=1,N)
      DO 200 I=1,N
      B(I)=B(I)*ADJK
      DO 200 J=1,N
      AK(I,J)=AK(I,J)*ADJK
  200 CONTINUE
      DELT=DELT/ADJK
      RETURN
      END
C
C
C
C
```

```
      SUBROUTINE SOLN
      DIMENSION P(20),Q(20),R(20),S(20),X(20)
      COMMON/BLK1/AK(20,20),AL(20,20),B(20),XN(20),XNM1(20),
     -     DELT,RTS,N,NTS,IOUT
      DO 100 I=1,N
      X(I)=XNM1(I)
  100 CONTINUE
      CALL ODE(X,P)
      DO 200 I=1,N
      X(I)=0.5*P(I)+XNM1(I)
  200 CONTINUE
      CALL ODE(X,Q)
      DO 300 I=1,N
      X(I)=0.5*Q(I)+XNM1(I)
  300 CONTINUE
      CALL ODE(X,R)
      DO 400 I=1,N
      X(I)=R(I)+XNM1(I)
  400 CONTINUE
      CALL ODE(X,S)
      DO 500 I=1,N
      XN(I)=XNM1(I)+(1.0/6.0)*(P(I)+2.0*Q(I)+2.0*R(I)+
     -     S(I))
      IF(XN(I).LT.0.0) XN(I)=0.0
  500 CONTINUE
      RETURN
      END
C
C
C
C
      SUBROUTINE ODE(X,DX)
      DIMENSION X(20),DX(20)
      COMMON/BLK1/AK(20,20),AL(20,20),B(20),XN(20),XNM1(20),
     .     DELT,RTS,N,NTS,IOUT
      DO 200 J=1,N
      SUM=0.0
      DO 100 I=1,N
      IF(I.EQ.J) GOTO 100
      SUM=SUM+AK(I,J)
  100 CONTINUE
      AL(J,J)=SUM
  200 CONTINUE
      DO 400 I=1,N
      SUM=0.0
      DO 300 J=1,N
      SUM=SUM+(AK(I,J)-AL(I,J))*X(J)
  300 CONTINUE
      DX(I)=(SUM+B(I))*DELT
  400 CONTINUE
      DO 500 I=1,N
      IF(X(I).LT.1.0) X(I)=1.0
  500 CONTINUE
      RETURN
      END
```

```
C
C
C
      SUBROUTINE OUT(I)
      COMMON/BLK1/AK(20,20),AL(20,20),B(20),XN(20),XNM1(20),
     .      DELT,RTS,N,NTS,IOUT
      IF(I.EQ.1) II=IOUT
      IF(II.NE.IOUT) GOTO 200
      II=0
      IF(I.EQ.1) II=1
      WRITE(7,100) I,(XN(J),J=1,N)
      WRITE(5,100) I,(XN(J),J=1,N)
  100 FORMAT(' ',I3,2X,10(F8.2,2X))
  200 CONTINUE
      II=II+1
      RETURN
      END
```

Part B

Primary Production Module

- Program Main - Controls program flow and calls subroutines.
- Subroutine Init - Zeroes and initializes arrays used in other subroutines.
- Subroutine PRIPRD - Performs final calculation of coefficient (eqs. 24 and 25).
- Subroutine RAD - Calculates hourly time series of incident solar radiation and total isolation for any point on earth and day of the year.
- Subroutine SUN - Calculates sun angles at specified time intervals for use in subroutine RAD.
- Subroutine CLOUD - Calculates cloud cover randomly chosen based on monthly means and variances.
- Function RAN - Generates random cloud cover used in Subroutine CLOUD.
- Subroutine NUT - Calculates nutrient limitation term.

```
MN
      COMMON/BLK1/ZDEPTH,S,T,EXTK,D,ROPTML,AVETMP,AMPTMP,HSCNIT,
     .CLPAR(12,2),NT,NZ
      COMMON/BLK2/CNIT,TEMP,PROD,PLCARB,JDATE(12)
      CALL OPEN(6,'PPCOEF  DAT',2)
      CALL INIT
      DO 1000 I = 1,365
      CALL PRIPRD(I)
      DO 2000 J = 1,12
      IF(I.NE.JDATE(J)) GOTO 2000
C     CALL OUT(I)
 2000 CONTINUE
 1000 CONTINUE
      STOP
      END
C
C
C
C
      SUBROUTINE INIT
      COMMON/BLK1/ZDEPTH,S,T,EXTK,D,ROPTML,AVETMP,AMPTMP,HSCNIT,
     .CLPAR(12,2),NT,NZ
      COMMON/BLK2/CNIT,TEMP,PROD,PLCARB,JDATE(12)
      DATA JDATE/1,32,60,91,121,152,182,213,244,274,305,335/
      DATA CLPAR/6.04,5.27,5.11,4.5,3.45,2.64,3.13,3.36,4.0,3.36,5.15,
     .     5.66,17.49,23.16,17.27,17.4,18.79,13.39,8.67,10.72,13.44,
     .     16.21,17.04,7.16/
      CNIT=1.0
      ZDEPTH=20.0
      S=2.0
      T=0.257
      EXTK=0.310
      D=20.0
      ROPTMN=300.0
      AVETMP=12.0
      AMPTMP=9.0
      HSCNIT=1.5
      NT=12
      NZ=21
      RETURN
      END
C
C
C
C
      SUBROUTINE PRIPRD(I)
      REAL NUTLIM,LOGMU
      COMMON/BLK1/ZDEPTH,S,T,EXTK,D,ROPTML,AVETMP,AMPTMP,HSCNIT,
     .CLPAR(12,2),NT,NZ
      COMMON/BLK2/CNIT,TEMP,PROD,PLCARB,JDATE(12)
      CALL RAD(I,RADLMZ)
      CALL NUT(NUTLIM)
      TIME=I
      ARG=2.0*3.1415927*(TIME-172.0)/365.0
      TEMP=AVETMP+AMPTMP*COS(ARG)
      LOGMU=0.0275*TEMP-0.070
      DOUBLE=10.0**LOGMU
      PMAX=2.0**DOUBLE-1.0
      PROD=PMAX*RADLMZ*NUTLIM
      WRITE(6,500) I,PROD
      WRITE(5,500) I,PROD
  500 FORMAT(' ',I3,2(F10.5,2X))
```

```
C
C
C
C
      SUBROUTINE RAD(I,RADLMZ)
      DIMENSION SUNANG(25),FAC(25),RADINC(25),FAC1(25)
      COMMON/BLK4/DEPTH,S,T,EXTK,D,ROPTM,AVETMP,AMPTMP,HSCNIT,
     .CLEAR(12,2),NT,NZ
      IF(I.NE.1)GO TO 100
      ARINM3=2.119
      ARINM2=0.319
      ARINM1=0.319
  100 CONTINUE
      RADOPT=0.7*ARINM1+0.2*ARINM2+0.1*ARINM3
      CALL SUN(I,PHOTOP,SUNANG)
      CALL CLOUD(I,CLD)
      RADCK=ROPTM/(PHOTOP*60.0)
      IF(RADOPT.LT.RADCK) RADOPT=RADCK
      DO 200 J=1,NT
      IF(SUNANG(J).LT.1.0) GO TO 210
      H=2.0*3.1415927*SUNANG(J)/360.0
      RADM=1.0/SIN(H)
      A=0.128-0.054*(ALOG10(RADM))
      RADICL=S*EXP(-T*A*RADM)*SIN(H)
      DIFF=0.44*EXP(-0.22*SUNANG(J))
      R=EXP(-0.149*SUNANG(J)*EXP(-0.014*SUNANG(J)))
      RADINC(J)=RADICL*(1.0-R+DIFF)*(1.0-0.071*CLD)
      GO TO 200
  210 CONTINUE
      RADINC(J)=0.0
  200 CONTINUE
      XN=NT-1
      DELH=PHOTOP*60.0/XN
      RADTOT=0.0
      DO 300 I=1,NT
      FAC(I)=RADINC(I)
      X=I
      Y=X/2.0
      IY=Y
      Z=IY
      IF(I.EQ.1) GO TO 330
      IF(I.EQ.NT) GO TO 330
      IF(Y.NE.Z) GO TO 310
      FAC(I)=4.0*FAC(I)
      GO TO 320
  310 CONTINUE
      FAC(I)=2.0*FAC(I)
  320 CONTINUE
  330 RADTOT=RADTOT+FAC(I)
  300 CONTINUE
      RADTOT=(DELH/3.0)*RADTOT
      CHLA=3.0
C     EXTK=EXTK+0.054*CHLA**(2/3)+0.0088*CHLA
      RADLIM=0.0
      DO 400 IZ=1,NZ
      DO 400 IT=1,NT
      DEPTH=IZ-1
      RADZ=RADINC(IT)*EXP(EXTK*DEPTH)
      RATIO=RADZ/RADOPT
      X1=IT
      Y1=X1/2.0
      IY1=Y1
      X1=IY1
      X2=IZ
```

```
      Y1=Y2
      IF(Y1.EQ.Y1) CONIT=4.0
      IF(Y2.EQ.Y2) CONIZ=4.0
      IF(Y1.NE.Y1) CONIT=2.0
      IF(Y2.NE.Y2) CONIZ=1.0
      IF(IT.EQ.1.OR.IT.EQ.NT) CONIT=1.0
      IF(IZ.EQ.1.OR.IZ.EQ.NZ) CONIZ=1.0
      CON=CONIT*CONIZ
      FUNC=RATIO*EXP(1.0-RATIO)
      RADLIM=RADLIM+CON*FUNC
  100 CONTINUE
      XNT=NT
      DELT=1.0/(XNT-1.0)
      XNZ=NZ
      DELZ=1.0/(XNZ-1.0)
      RADLMT=(DELT*DELZ/9.0)*RADLIM
      AVERAD=(RADTOT/(PHOTOP*60.0))*EXP(EXTK)
      ARDNM3=ARDNM2
      ARDNM2=ARDNM1
      ARDNM1=AVERAD
      RETURN
      END
C
C
C
C
      SUBROUTINE SUN(I,PHOTOP,SUNANG)
      DIMENSION SUNANG(25)
      COMMON/BLK4/ZDEPTH,S,T,EXTK,D,ROPTML,AVETMP,AMPTMP,HECNIT,
     .CLEAR(12,2),NT,NZ
      H=6.0
      TIME=I
      ARG=(2.0*3.1415927*(TIME-172.0))/365.0
      SUNLAT=23.5*COS(ARG)
      P=2.0*3.1415927*(90.0-SUNLAT)/360.0
      OR=2.0*3.1415927*O/360.0
      ARG1=0.5*(P+OR-H)
      ARG2=0.5*(P-OR+H)
      HAVT=(1.0/SIN(P))*(1.0/COS(OR))*SIN(ARG1)*COS(ARG2)
      COSA=1.0-2.0*HAVT
      TA=COSA/SQRT(1.0-COSA**2)
      SOLHA=1.570796-ATAN(TA)
      SOLHA=SOLHA*360.0/(2.0*3.1415927)
      PHOTOP=2.0*SOLHA/15.0
      SUNRIS=12.0-SOLHA/15.0
      SUNSET=12.0+SOLHA/15.0
      DO 100 K=1,NT
      XN=(NT-1)/2
      XI=K-1
      TIME=12.0-(SOLHA-XI*SOLHA/XN)
      T1=2.0*3.1415927*TIME/24.0
      SINHA=SIN(P)*COS(OR)*COS(T1)+(COS(P)*SIN(OR))
      TA=SINHA/SQRT(1.0-SINHA**2)
      SUNANG(K)=ATAN(TA)
      SUNANG(K)=SUNANG(K)*360.0/(2.0*3.1415927)
      IF(K.EQ.1) SUNANG(K)=0.0
      IF(K.EQ.NT) SUNANG(K)=0.0
  100 CONTINUE
      RETURN
      END
C
C
C
      SUBROUTINE CLOUD(I,CLD)
```

```
      IF(I.EQ.1)SAVE=100.0
      [illegible]
      IF(I.GE.1.AND.I.LE.31)IT=1
      IF(I.GE.32.AND.I.LE.59)IT=2
      IF(I.GE.60.AND.I.LE.90)IT=3
      IF(I.GE.91.AND.I.LE.120)IT=4
      IF(I.GE.121.AND.I.LE.151)IT=5
      IF(I.GE.152.AND.I.LE.181)IT=6
      IF(I.GE.182.AND.I.LE.212)IT=7
      IF(I.GE.213.AND.I.LE.243)IT=8
      IF(I.GE.244.AND.I.LE.273)IT=9
      IF(I.GE.274.AND.I.LE.304)IT=10
      IF(I.GE.305.AND.I.LE.334)IT=11
      IF(I.GE.335.AND.I.LE.365)IT=12
      SEED=ABS(SAVE)
      XBAR=CLPAR(IT,1)
      XVAR=CLPAR(IT,2)
      CLD=RAN(SEED,XBAR,XVAR)
      SAVE=CLD
      IF(CLD.LT.0.0) CLD=0.0
      IF(CLD.GT.10.0) CLD=10.0
      RETURN
      END
C
C
C
C
      FUNCTION RAN(SEED,XBAR,XVAR)
      T1=199017.0
      T2=24298.0*SEED+99991.0
      T2=AMOD(T2,T1)
      X1=T2/T1
C
      T2=24298.0*T2+99991.0
      T2=AMOD(T2,T1)
      X2=T2/T1
C
      T1=-2.0*ALOG(X2)
      T1=SQRT(T1)
      T2=2.0*3.1415927*X1
      T2=COS(T2)
      XSI=SQRT(XVAR)
      T2=T1*T2
      RAN=T2*XSI+XBAR
      RETURN
      END
C
C
C
C
      SUBROUTINE NUT(NUTLIM)
      REAL NUTLIM
      COMMON/BLK1/ZDEPTH,S,T,EXTK,D,ROPTMN,AVETMP,AMPTMP,HSCNIT,
     .CLPAR(12,2),NT,NZ
      COMMON/BLK2/CNIT,TEMP,PROD,PLCARB,IDATE(12)
      NUTLIM=CNIT/(HSCNIT+CNIT)
      NUTLIM=1.0
      RETURN
      END
```

Part C

Input-Output Flow Analysis Module

- Program Main - Computes and outputs intermediate matrices and input-output values.
- Subroutine MMULT - Performs all matrix multiplications.

```
      DIMENSION ZZ(10,10),YY(10,10),XZY(10,10),APPI(10,10),API(10,10),
     .          Z(10),Y(10),X0(10),XN(10),XPP(10,10),XP(10,10),
     .          CHIPP(10,10),CHIP(10,10),CHIPT(10,10),SAVE(10,10)
      CALL OPEN(6,'BOFIN1  DAT',2)
      CALL OPEN(7,'BOFIN2  DAT',2)
      CALL OPEN(8,'BOFOUT  DAT',2)
C
      DO 1000 II=1,4
      N=10
      DO 25 I=1,N
      DO 25 J=1,N
      ZZ(I,J)=0.0
      YY(I,J)=0.0
   25 CONTINUE
      DO 100 I=1,N
      READ(6,50) (APPI(I,J),J=1,N)
   50 FORMAT(1X,10(F10.5,2X))
  100 CONTINUE
      DO 150 I=1,N
      READ(6,50) (API(I,J),J=1,N)
  150 CONTINUE
C
      READ(7,200) (Z(I),I=1,N)
      READ(7,200) (Y(I),I=1,N)
      READ(7,200) (X0(I),I=1,N)
      READ(7,200) (XN(I),I=1,N)
  200 FORMAT(1X,10F7.2)
C
      DO 250 I=1,N
      DO 250 J=1,N
      SAVE(I,J)=API(I,J)
  250 CONTINUE
      DO 275 I=1,N
      DO 275 J=1,N
      API(I,J)=SAVE(J,I)
  275 CONTINUE
C
      DO 300 I=1,N
      ZZ(I,I)=Z(I)
      YY(I,I)=Y(I)
      DO 300 J=1,N
      APPI(I,J)=-APPI(I,J)
      API(I,J)=-API(I,J)
  300 CONTINUE
C
      CALL MMULT(N,N,N,APPI,ZZ,XPP)
      CALL MMULT(N,N,N,API,YY,XP)
C
      DO 310 I=1,N
      X0(I)=0.0
      XN(I)=0.0
  310 CONTINUE
C
      DO 320 I=1,N
      DO 320 J=1,N
      X0(I)=X0(I)+XPP(I,J)
      XN(I)=XN(I)+XP(I,J)
  320 CONTINUE
C
      DO 400 I=1,N
      DO 400 J=1,N
```

```
      CHIPP(I,J)=0.0
      CHIP(I,J)=0.0
      IF(X0(I).NE.0.0) CHIPP(I,J)=XPP(I,J)/X0(I)
      IF(XN(I).NE.0.0) CHIP(I,J)=XP(I,J)/XN(I)
  400 CONTINUE
C
      DO 450 I=1,N
      DO 450 J=1,N
      SAVE(I,J)=CHIP(I,J)
  450 CONTINUE
      DO 475 I=1,N
      DO 475 J=1,N
      CHIPT(J,I)=SAVE(I,J)
  475 CONTINUE
C
      CALL MMULT(N,N,N,CHIPT,CHIPP,XZY)
C
      DO 480 I=1,N
      DO 480 J=1,N
      X0(I)=0.0
  480 CONTINUE
      DO 485 I=1,N
      DO 485 J=1,N
      X0(I)=X0(I)+XZY(I,J)
  485 CONTINUE
      DO 490 I=1,N
      DO 490 J=1,N
      IF(X0(I).NE.0.0) XZY(I,J)=XZY(I,J)/X0(I)
  490 CONTINUE
C
      DO 600 I=1,N
      WRITE(8,500) (XPP(I,J),J=1,N)
  500 FORMAT(' ',10(F11.7,1X))
  600 CONTINUE
      WRITE(8,610)
  610 FORMAT(' ',/)
C
      DO 625 I=1,N
      WRITE(8,500) (XP(I,J),J=1,N)
  625 CONTINUE
      WRITE(8,610)
C
      DO 650 I=1,N
      WRITE(8,500) (CHIPP(I,J),J=1,N)
  650 CONTINUE
      WRITE(8,610)
C
      DO 675 I=1,N
      WRITE(8,500) (CHIP(I,J),J=1,N)
  675 CONTINUE
      WRITE(8,610)
C
      DO 700 I=1,N
      WRITE(8,500) (XZY(I,J),J=1,N)
  700 CONTINUE
      WRITE(8,610)
      WRITE(8,710)
  710 FORMAT(' ',/////)
C
 1000 CONTINUE
      STOP
      END
C
C
```

```
      SUBROUTINE MMULT(N1,M1,M2,X,Y,Z)
      DIMENSION X(10,10),Y(10,10),Z(10,10)
      WRITE(5,10)
   10 FORMAT(' MULTI MAT')
      N2=M1
CC
      DO 200 IR=1,N1
      DO 200 JC=1,M2
      SUM=0.0
      DO 100 IXC=1,M1
      JYR=IXC
      SUM=SUM+X(IR,IXC)*Y(JYR,JC)
  100 CONTINUE
      Z(IR,JC)=SUM
  200 CONTINUE
      RETURN
      END
```